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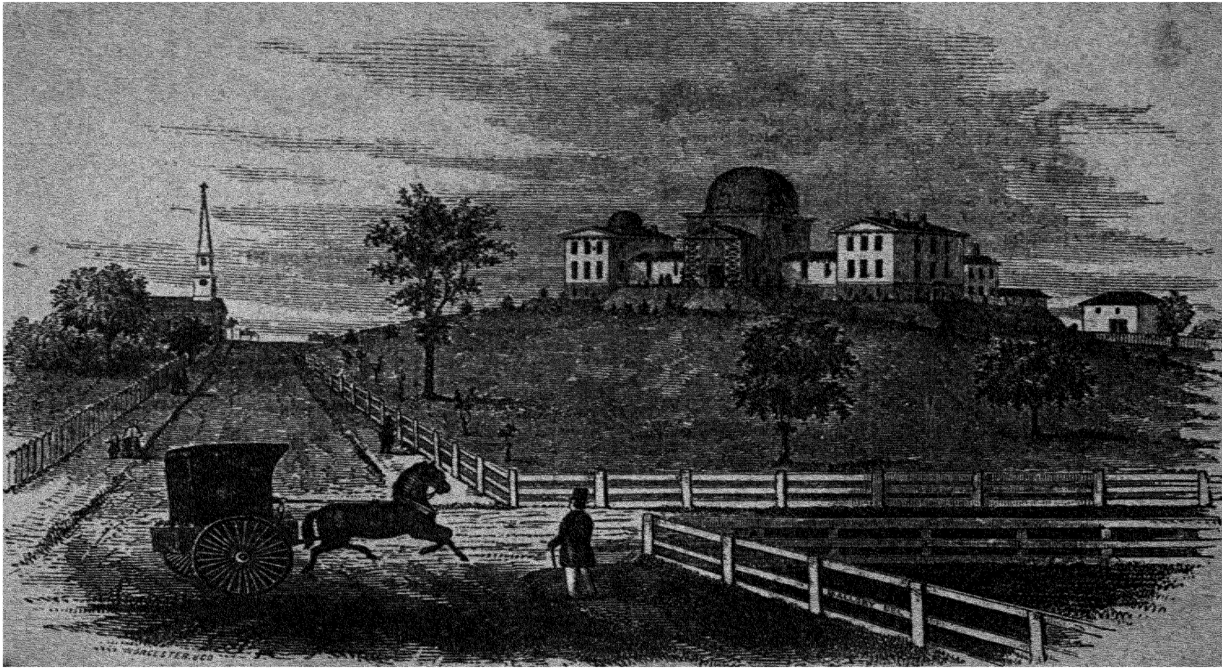
THE HISTORY AND WORK OF HARVARD OBSERVATORY

1839 to 1927



THE HARVARD OBSERVATORY IN 1852.

Frontispiece

HARVARD OBSERVATORY MONOGRAPHS

No. 4

The History and Work of Harvard Observatory

1839 to 1927

An Outline of the Origin, Development, and Researches of the Astronomical Observatory of Harvard College together with Brief Biographies of Its Leading Members

BY

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Published for the Observatory by the

McGRAW-HILL BOOK COMPANY, Inc.

NEW YORK AND LONDON

1931

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE

THIS book has been prepared at the suggestion of Dr. Harlow Shapley, Director of the Harvard College Observatory. Indeed, a similar request had been made several years earlier by Professor E. C. Pickering, the preceding director. The author has been associated with the Observatory since 1887 and during this time has had favorable opportunities to become familiar with its varied activities. From the limitations imposed by the size of the volume, little more than an outline of the subjects presented has been possible. In Section II a discussion is given of only the more important researches undertaken by the members of the Observatory. An account of many investigations of which no explicit mention is made in this book may be found by reference to the publications enumerated in Chapter VI.

The author acknowledges the assistance which has been generously given him by other members of the Observatory Staff, by Professors Edward S. King and Willard P. Gerrish, Dr. Willard J. Fisher, Mr. Leon Campbell, Dr. Annie J. Cannon, Mrs. Doris M. Wills, Miss Constance D. Boyd, and especially Dr. Cecilia H. Payne and Dr. Harlow Shapley.

S. I. B.

CAMBRIDGE, MASS.,
April, 1931.

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THE ANCESTRY OF THE HARVARD OBSERVATORY

THE Harvard Observatory was established by an official act of the Corporation of Harvard University in October, 1839. The first director (who possessed the title of Astronomical Observer) was appointed at that time and observations were begun at the end of that year. A number of other astronomical observatories were founded in the United States in the first half of the nineteenth century as a result of the general quickening of scientific interest; but the beginnings of that interest appeared much earlier, and were intimately connected with Massachusetts and with Harvard University.

In spite of the difficulty of direct communication with European centers of thought, an interest in astronomical science and discovery was by no means lacking in the Massachusetts Bay Colony during the first century after its settlement. European astronomy was still in its childhood; the Paris Observatory was not founded until 1667, and the Greenwich Observatory, not until 1675. Galileo died in 1642, the year of Newton's birth, and six years after Harvard College was founded. Newton's discoveries, though announced during the last half of the seventeenth century, were not generally familiar to the scientific world until the beginning of the eighteenth. The Royal Astronomical Society was not founded until 1820.

Foundation of Harvard College.—The Massachusetts Bay Colony was founded about 1630. It is remarkable that within its first decade, in 1636, this pioneer colony, by a vote of its elected representatives, established a college for the education of its youth. The college thus founded as a public charge was early called Harvard College, after John Harvard, its first private benefactor. It was intended especially to teach and to perpetuate the religious doctrines of the early settlers. A liberal spirit, nevertheless, breathed through the official act.

After God had carried us safe to New England, and we had builded our houses, provided necessaries for our liveli-hood, rear'd convenient places for God's worship, and settled the Civill Government, one of the next things we longed for, and looked after was to advance learning, and perpetuate it to Posterity: dreading to leave an illiterate Ministry to the Churches, when our present Ministers shall lie in the Dust.

The name of the town in which the college was placed was changed from Newtown to Cambridge in 1638. Instruction was begun in the same year, the first building having been erected in 1637. For a long time the faculty of the College consisted of a president and two or three tutors; yet even in those early days astronomy was held in considerable esteem. In 1642, the year of the first Commencement ceremonies, according to "The Laws, Liberties and Orders of Harvard College," it was declared that:

10. Every Scholar that giveth up in writing a synopsis or summary of Logic, Natural and Moral Philosophy, Arithmetic, Geometry, and Astronomy, and is ready to defend his theses or positions, withal skilled in the originals as aforesaid, and still continues honest and studious, at any public act after trial, he shall be capable of the second degree, of Master of Arts.[1]

Astronomy was not required for the lower degree of bachelor.

During the first century after its foundation, the struggle and poverty of a pioneer community had their inevitable effects on the life of the College, which was dependent, in large part,

[1] Josiah Quincy, History of Harvard University, 1, 517, 1840.

on special state grants for its equipment and maintenance. In addition to these difficulties there was almost continuous dissension between the deep but narrow and dominating religious spirit of the times, and the more liberal element which was never lacking. As President Quincy says: "Of all persecutors, politicians whose power depends upon a display of religious zeal, are naturally the most bitter."[2]

Early Astronomy in Massachusetts.—Such an atmosphere was evidently none too favorable for the pursuit of astronomical science. Something was nevertheless attempted, and real contributions to science were made by such men as Thomas Brattle. Born in 1657, he was graduated from Harvard College in 1676, and was Treasurer of the College for 20 years. He was distinguished among his contemporaries for his scientific attainments:

> Bailey in his supplement to the account of Flamsteed, states, that "Mr. Thomas Brattle, of Boston in New England, is the anonymous person alluded to by Newton, in his *Principia*, as having made such good observations on the comet of 1680."[3,4]

Mr. Brattle also observed the solar eclipse of June, 1694, and the lunar eclipses of February, 1700, and December, 1703.[5] Among the transactions of the Royal Society of London is a communication entitled "Observatio Eclipsis Lunaris peracta Bostonii Novanglorum, die quinto Aprilis, Vespere, A. D. 1707, a Tho. Brattle."[6] William Brattle, son of Thomas Brattle, was a Fellow of the Royal Society of London, and, like his father, a man of scientific tastes.

Although astronomy appears to have been taught since the beginning of instruction at Harvard College, a professorship of mathematics and natural philosophy was first established

[2] *Ibid.*, p. 335.

[3] *Ibid.*, p. 412. By "Bailey," Francis Baily is meant.

[4] Newton, Philosophiae Naturalis Principia Mathematica (Geneva Edition), 3, 633, 634, 635, 638, 1742.

[5] Phil. Trans. Roy. Soc. (abridged), **5**, 148, 1704.

[6] *Ibid.*, **5**, 379, 1707.

there in 1727, through the generosity of Mr. Thomas Hollis. The first appointment to this professorship seems to have been an unfortunate one, but in 1738 John Winthrop, friend of Benjamin Franklin, able scientist, and lover of astronomy, was chosen for the position. Two years later he communicated to the Royal Society of London a paper entitled "Observations of the Transit of Mercury over the Sun."[7] These observations were published in the Transactions[8] and were favorably noticed in the Memoirs of the Royal Academy of Arts and Sciences at Paris.

The Venus Expedition of 1761.—Observations of the transit of Venus in 1761 were desired, and

> Professor Winthrop was inspired with an intense desire to assist in accomplishing this important object; and, as the transit was not visible in the latitude of New England, he determined, if possible, to observe it from Newfoundland. He therefore addressed a memorial to Governor Bernard, who, entering cordially into his views, by a special message on the subject, obtained from the Massachusetts Legislature leave to place the Province sloop at his service for this purpose.[9]

The plan was carried out successfully. Professor Winthrop, with such apparatus suitable to his purpose as was in the possession of the College, went to Newfoundland and observed the transit on June 6, 1761. The expedition is worthy of special attention, since it shows that astronomical interest was strong in Massachusetts even at this early date.

The transit of 1769 was also observed by Winthrop, who was doubtless placed at some disadvantage by the disastrous fire of 1764, referred to on page 7. This transit was visible, however, over the eastern United States and was well observed in Pennsylvania by Rittenhouse and others. Although Rittenhouse lacked the early educational and social advantages of Winthrop, his native genius and his modesty brought him a wide reputation, and the friendship of Washington, Franklin,

[7] Josiah Quincy, *op. cit.*, **2**, 25.
[8] Phil. Trans. Roy. Soc. (abridged), **8**, 713, 1743.
[9] Josiah Quincy, *op. cit.*, **2**, 22.

and other eminent men of the day. He was eighteen years younger than Winthrop. Although both astronomers were members of the American Philosophical Society of Philadelphia, they appear to have been but slightly acquainted, and little correspondence passed between them.

Career of John Winthrop.—Winthrop has been called the first American astronomer. Belonging to one of the oldest and most prominent families in New England, he enjoyed the best social and educational advantages that Massachusetts could offer. The duties of his professorship occupied the greater part of his time, but he took part in many scientific investigations in mathematics, meteorology, and geodesy, as well as in astronomy. He made no great discoveries but he gained a wide reputation both in this country and abroad. He was elected a Fellow of the Royal Society in 1765, and member of the American Philosophical Society in 1768. He received the degree of LL.D. from Edinburgh in 1771, and from Harvard in 1773, the first time that degree had been awarded at Harvard University. Winthrop died in 1779 at the age of sixty-five years.

Under Winthrop's guidance, scientific observation and the teaching of astronomy at Harvard attained real importance. Both, however, were seriously retarded by the disastrous fire that consumed Harvard Hall and all the instruments it contained on the night of January 24, 1764.

For Astronomy, we had before been supplied with telescopes of different lengths; one of 24 feet; and a brass quadrant of 2 feet radius, carrying a telescope of a greater length, which formerly belonged to the celebrated Dr. Halley. We had also the most useful instruments for dialling; and, for surveying, a brass semi-circle with plain sights and magnetic needle. Also, a curious Telescope, with a complete apparatus for taking differences of level . . . [list of several donors] . . . From these gentlemen we received fine reflecting telescopes of different magnifying powers, and adapted to different observations; Microscopes of the several sorts now in use; Hadley's quadrant, fitted in a new manner; a nice variation compass, and dipping needle; with instruments for the several magnetical

and electrical experiments,—all new and of excellent workmanship.—*All destroyed!*[10]

Foundation of The American Academy.—The American Academy of Arts and Sciences was founded in 1780, while the American Revolution was in progress. In 1785, the first volume of the Memoirs was published. On page viii of the Preface the editor states that:

> The Astronomical and mathematical papers in the volume will, perhaps, be the least entertaining of any in the collection, and will have the smallest number of readers. However, they are useful in such a work. Few, if any of them, contain deep speculations and abstruse researches and calculations; but they are chiefly of the practical kind . . . These, and all other mathematical pieces will be gratefully received, and due attention paid to them by this body.

The volume contains 14 astronomical papers, which deal with the determination of the difference in longitude between Harvard Hall and Greenwich, the latitude of Cambridge, the transit of Mercury in 1782, the solar eclipse of 1780, and various other subjects. For many years astronomy had evidently received much attention in Boston and the vicinity, and especially at Harvard College. Of special significance is the paper by Reverend Joseph Willard, President of Harvard University, entitled "A Memoir Containing Observations of a Solar Eclipse, October 27, 1780, made at Beverly; also, of a Lunar Eclipse, March 29, 1782, of a Solar Eclipse, April 12, and of the Transit of Mercury over the Sun's Disc, November 12, the same year, made at the President's House in Cambridge."[11]

The Harvard Eclipse Expedition of 1780.—In May, 1780, Reverend Samuel Williams was installed Hollis Professor of Mathematics and Natural Philosophy. A paper by him appears in the first volume of the Memoirs, giving an account of his various astronomical observations made from 1761 to 1784. The paper includes a description of the solar eclipse of

[10] *Ibid.*, p. 483.

[11] Mem. Amer. Acad., 1, 129, 1785

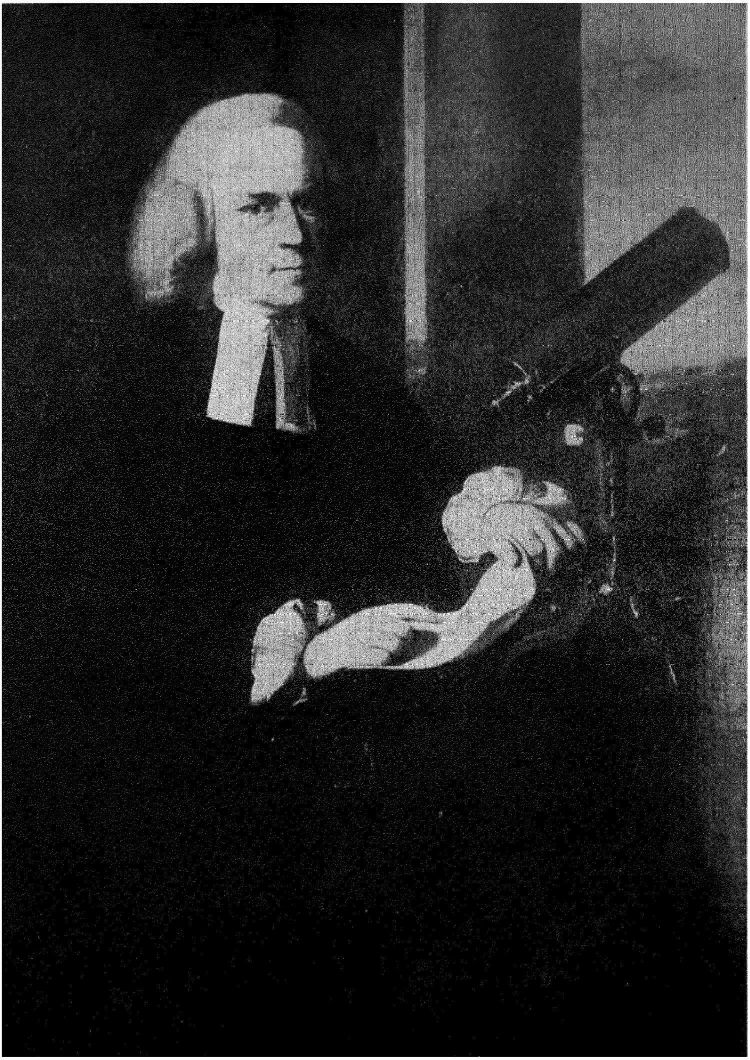

PLATE I.—JOHN WINTHROP. (From a painting by Copley in the Faculty Room, University Hall, Harvard University.)

(*Facing page 8*)

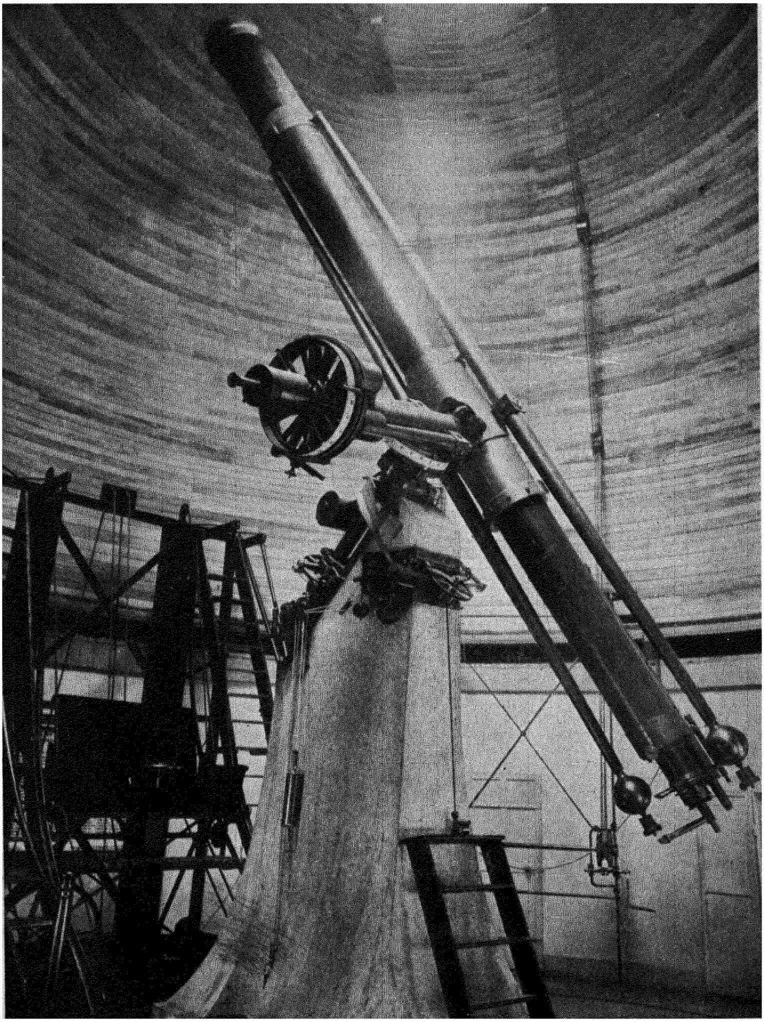

PLATE II.—THE 15-INCH REFRACTOR.

1780, already mentioned, as observed by him at Penobscot Bay in the present State of Maine, then a part of Massachusetts. The Colonies were at this time at war with Great Britain, but, for the second time in the history of Massachusetts a public subsidy of the eclipse expedition bore witness to the value that was placed upon astronomical observation. In regard to this expedition Professor Williams states:

> A favorable opportunity for viewing one of these eclipses occurring on October 27, 1780, the American Academy of Arts and Sciences, and the University at Cambridge, were desirous to have it properly observed in the eastern part of the State, where, by calculation, it was expected it would be total. With this view they solicited the Government of the Commonwealth, that a vessel might be prepared to convey proper observers to Penobscot-Bay; and that application might be made to the officer who commanded the British garrison there, for leave to take a situation convenient for the purpose. Though involved in all the calamities and distresses of a severe war, the Government discovered all the attention and readiness to promote the cause of science, which could have been expected in the most peaceable and prosperous times; and passed a resolve, directing the Board of War to fit out the Lincoln Galley to convey me to Penobscot, or any other part at the eastward, with such assistants as I should judge necessary.[12]

There was evidently much enthusiasm for the expedition, and volunteers were numerous. Professor Williams selected as his assistants Professor Sewall, Mr. Winthrop (librarian), Mr. Vernon (a graduate), and Messrs. Atkinson, Davis, Hall, Dawson, Rensselaer, and King, students in the College.

Although the British officer in command at Penobscot Bay permitted the expedition to land, he imposed time limits which were so brief as to afford small opportunity for preparing the camp or for determining its position. The position of the site was incorrectly given on the maps of the time, so that an error of half a degree was made in its selection, and the eclipse therefore appeared not quite total. Professor Williams deserves no discredit for the error, and he seems to have made the best of very difficult circumstances.

[12] *Ibid.*, p. 86.

Bowditch and Sumner.—The active and widely extended interest in astronomical problems, long present in Massachusetts, bore witness to the enduring influence of the large element of University graduates among the early colonists. An immense impetus to the scientific development of the colony was also given by a few men of genius. Benjamin Franklin and Benjamin Thompson (Count Rumford) were born in Massachusetts and passed their earliest years here, and their influence cannot have failed to foster a broader scientific outlook.

Among those in Massachusetts whose influence was greatest in the development of mathematics and astronomy, and in the establishment of the Harvard Observatory, was Nathaniel Bowditch (1773 to 1838). He was born in humble circumstances, of New England stock, had few educational advantages in youth, and was almost entirely self-taught. While young he made five sea voyages, during which he devoted every spare moment to study. His enthusiasm was contagious—on one ship every sailor, and even the cook, learned the art of navigation and could determine the position of the vessel with sufficient precision.

Bowditch was the author of many astronomical papers, in addition to his famous "New American Practical Navigator," and his translation of the "Mécanique Céleste" of Laplace. Of this translation Legendre wrote, in 1832: "Your work is not merely a translation with a commentary; I regard it as a new edition, augmented and improved, and such as might have come from the hand of the author himself."

Bowditch gained an international reputation in astronomy and was deeply interested in the development of the science, especially at Harvard. He was offered the position of Hollis Professor of Mathematics and Natural Philosophy in 1806; he also received flattering offers from different parts of the country, all of which he declined. Harvard University conferred on him the degree of LL.D. in 1816.

Another name prominent in the history of navigation is that of Captain Thomas H. Sumner, an American shipmaster.

In 1843, Sumner published at Boston "A New and Accurate Method of Finding a Ship's Position at Sea." The discovery of this method proved to be of incalculable value to navigation. Its essential feature consisted in the proof that a single observation of the sun's altitude determines the ship's position as somewhere on a line—the "Sumner line"—whose direction is readily determined. (This line is really a part of the so-called "circle of position," but for convenience may be regarded as a straight line at any point.) In America, Sumner's method received the unqualified approval of Benjamin Peirce, and in Europe, that of Lord Kelvin and others. A similar method had already been tried, it is claimed, by officers of the British Navy, but even if the claim is justified, the method remained of little use until it had been simplified and made practical by Sumner. The details of this method were later considerably modified.

The Harvard Observatory First Planned.—John Quincy Adams, sixth President of the United States, was highly influential in bringing about the establishment of the Harvard Observatory. He also aided greatly in the development of astronomy elsewhere, especially in forwarding the foundation of the National Observatory at Washington, and in the dedication of the Cincinnati Observatory founded by General O. M. Mitchel and built by the citizens of that city. To Josiah Quincy, President of the University from 1829 to 1845, should be given equal honor, as will be seen in subsequent pages.

The remarkable interest in astronomy, so well indicated by the establishment of many observatories in America in the first half of the nineteenth century, was fostered by the great and even spectacular events and discoveries of the time. Uranus was discovered in 1781, and was an object of great popular as well as scientific interest. Neptune was not found until 1846, by the labors of Leverrier and Adams, but the nature of the problem involved was by no means original with them, and had been in the minds of astronomers for more than

20 years. Several satellites, or moons, had also been discovered in the solar system; four minor planets were discovered early in the nineteenth century; comets of great brilliancy, especially Halley's comet at the return of 1835, fanned the public interest; the meteor shower of 1833 was a most spectacular event. The total eclipse of the sun in 1806 was the means of turning the life of William Cranch Bond into astronomical lines. The first authoritative determination of the distance of a star was made in 1837 for 61 Cygni. These various events made a strong appeal to all intelligent men.

Just when the idea was first conceived of establishing an astronomical observatory for Harvard University cannot be determined with certainty. It was probably not later than the closing years of the eighteenth century, for:

> As early as the year 1805, we find Mr. John Lowell, at that time residing in Paris, consulting with the French astronomer, Delambre, on the subject of astronomical observatories, and procuring from him written instructions in regard to suitable buildings and instruments. The information thus gathered was transmitted to Mr. Webber, at that time Hollis Professor of Mathematics and Natural Philosophy in Harvard College, from which we conclude that the purpose of erecting an observatory was then under serious consideration by friends of the College. It does not appear, however, that any official action was taken upon the subject at that time. It was ten years later that the Corporation adopted active measures for the promotion of this object, when, at a meeting of the President and Fellows, held May 10th, 1815, present, the President [Dr. Kirkland], Dr. Lathrop, Hon. Christopher Gore, Judge Davis, Hon. John Lowell, Judge Phillips,—it was "*Voted*, That the President, Treasurer, and Mr. Lowell, with Professor Farrar and Mr. Bowditch, be a committee to consider upon the subject of an observatory, and report to the Corporation their opinion upon the most eligible plan for the same and the site."[13]

This was probably the first corporate act passed in the United States having for its object the establishment of an astronomical observatory.

A subcommittee consisting of Professor Farrar and Dr. Bowditch was afterward appointed to attend especially to the subject. Mr. William Cranch Bond, a Boston clock

[13] H. A., I, ii, 1856.

maker and amateur astronomer, was about to make a trip to Europe, and, on June 23, 1815, he was requested by the chairman of the Committee, Professor Farrar, to make a careful study of the Greenwich Observatory, and:

Also, inquire of Troughton the price of an eight-foot transit instrument of the best construction for an observatory, and the price of an eight-foot circular instrument of the kind lately made for the Observatory at Greenwich, and how soon these two instruments can be completed upon being ordered. The prices of the best clocks for observatories, and how soon one can be made, and the price of a heliostatic movement for a telescope.

I would observe further, that, with regard to the sort of information which we wish you to bring with you, in order to answer our purpose, it must be such as to enable you or some other person to superintend and direct in the erection of an observatory.[14]

These instructions were faithfully carried out by Mr. Bond, and on his return he had a model dome constructed at his own expense, on the same plan as that later used for the large dome of the 15-inch refractor. A discussion of the mass of information collected by Mr. Bond and that received from other sources showed that the expense of establishing and maintaining a well-equipped observatory would greatly exceed the estimates that had previously been made. An unsuccessful appeal to some wealthy friends of the plan proved that the time was not ripe for its execution.

The design was revived in 1822, and the same committee examined various positions in the vicinity of the college, for the purpose of selecting the most suitable for an observatory. A report was made very favorable to a position in that vicinity, on land owned by Edmund Dana, and an authority was given to purchase two acres and a half for that purpose. The negotiations, however, failed, and further proceedings were postponed.

In October, 1823, John Quincy Adams, then Secretary of State of the United States, addressed a letter to a member of the Corporation, urging that a building should be erected, without waiting for instruments from Europe, and recommending that the site nearest the College should be selected, even should it occasion some addition to the expense; proximity to the College being, in his judgment, important to the health and comfort of both the professor and the students, as the night and the winter are

[14] *Ibid.*, iii.

the time and season specially adapted to astronomical observations. Mr. Adams strongly recommended a subscription to be opened for the purpose, and, upon condition that the requisite sum should be raised in two years, authorized a thousand dollars to be put down on his account, but requesting his name to be concealed. The attempt, however, did not succeed. In October, 1825, the time limited in his former subscription having expired, he wrote again, to the same member of the Corporation, on the subject, urged a renewal of the attempt, and renewed his offer of one thousand dollars, on the same conditional limitation of two years. About this time, an address to the public was prepared and published, and a subscription opened, but in the result proved insufficient.[15]

President Kirkland, in his Annual Report for 1825 to 1826 to the Overseers of Harvard University, made a strong appeal for the establishment of a professorship of astronomy at the University, together with an astronomical observatory, stating that such action would establish the first observatory in the American hemisphere. This appeal appears to have met with no response.

Foundation of the Harvard Observatory.—For 13 years the hope of establishing an observatory lay dormant. The events that finally led to their realization are best related in the words of President Quincy, who had a deep interest in the plans, and who wrote in 1840, before the Observatory had been removed from its original site:

No further active endeavor (since 1825) was made for this object until the autumn of 1839. During the interval, the land formerly selected as a site for the observatory had been purchased, and thus one great requisite for success was attained. The house on this land was also large and commodious; the site for the observatory the best in the immediate vicinity of the College, and satisfactory. When the subject was communicated to the friends of the design, their opinion was unanimous, that the opportunity was highly favorable for its commencement. Funds adequate to the buildings immediately requisite having been readily obtained, the house was furnished with all the additions that were needed to fit it for its intended purpose.

The Observatory has now at its command, from the College apparatus and the instruments belonging to Mr. Bond, a transit instrument and

[15] Josiah Quincy, *op. cit.*, 2, 567, 1840.

variation transit, by Troughton and Symms; an astronomical clock, one refracting and two reflecting telescopes; an astronomical quadrant, by Bird; Gauss' magnetometer; a small transit, by Bird; a quadrant and sextant, with chronometers, thermometers, barometers, hygrometers, dipping and variation needles. To render the observatory as efficient as could be desired, there is wanted a refracting telescope equatorially mounted, a mural circle, and a large transit instrument. These, it cannot be questioned, will soon be supplied in some form, by the liberality of the public or individuals, as soon as the advance already made towards a sufficient apparatus for an observatory shall be understood and realized.

Although the apparatus possessed by Mr. Bond was excellent, and sufficient for the observations in which he was engaged in connection with the Exploring Expedition, yet it was not expressly adapted to the purposes indicated by the Royal Society of Great Britain, in their address to the several scientific societies in Europe and America, on the subject of a conjoined and contemporaneous series of observations on meteorology and the elements of the magnetic power; and the American Academy of Arts and Sciences, in Boston, being desirous to coöperate with the Royal Society of Great Britain on this subject, and to aid, also, the exertions in this direction of the Corporation of Harvard College, appropriated one thousand dollars for the purchase of the requisite instruments, in conformity with the suggestions and request of the Royal Society, deposited them in the rooms of the University, and placed the whole at the disposal of Professor Lovering and Mr. Bond, and have thus enabled the College early to become one of the few magnetic stations yet established on this side of the Atlantic.

A regular series of observations is now, and for these eight months has been making, by Mr. Bond, and Professor Lovering, with the valuable assistance of Benjamin Peirce, the University Professor of Mathematics, a publication of some of which, it is expected, will soon commence, and be afterwards regularly communicated to the public.[16]

Thus did the Harvard College Observatory come into being. Its future was placed in the hands of William Cranch Bond. The time and manner of the engagement of Mr. Bond by the Corporation can also best be told in the words of President Quincy:

In October, 1839, the Corporation were informed that Mr. William Cranch Bond was engaged, under an appointment and contract with the Government of the United States, with a well-adapted apparatus, in a

[16] *Ibid.*, p. 567.

series of observations on "meteorology, magnetism, and moon-culminations, as also upon all the eclipses of the sun and moon and Jupiter's satellites," in connexion with those which should be made by the officers of the expedition to the South Sea, commenced in 1838, under the authority of Congress, for the determination of longitude and other scientific purposes. Being also apprized of the reputation sustained by Mr. Bond as a skillful, accurate, and attentive observer, they made arrangements with him, with the consent of the Government of the United States, for the transfer of his whole apparatus to Cambridge, appointed him Astronomical Observer to the University and took measures to raise by subscription a sufficient sum to erect such buildings as were immediately required.[17]

[17] *Ibid.*, p. 391.

CHAPTER II

THE OBSERVATORY AT THE DANA HOUSE

For about four years the newly established Observatory remained at the Dana House. The main building, more recently referred to as the Dana-Peabody House, was probably built by Thomas Foster, who purchased a part of the old Dana estate; it still stands in the southeast part of the College inclosure near the corner of Quincy Square and Quincy Street. It was occupied as a dwelling by Richard H. Dana, the poet, from 1822 to 1832, and later by President Felton, and Professors Peabody and Palmer. A cupola on this house was provided with a dome for the use of the principal observing instrument, a reflecting telescope. The instruments then in the possession of the College were useful for teaching rather than for research.

The Early Astronomical Equipment.—Bond brought with him from Dorchester his own instruments with which he had for some time been making observations for the Government of the United States. These observations were continued in Cambridge. His instruments included two small telescopes—a reflector and a refractor—a 2¾-inch transit instrument made by Troughton and Simms, and two excellent clocks. Bond and his family lived in the Dana House and one room was occupied by an astronomical clock, a sidereal chronometer, a standard barometer, and three auxiliary barometers. The transit instrument was placed in an adjacent building made especially for it on a foundation of massive construction, according to Bond's usual methods. A meridian mark was placed on a stone pier of solid masonry on the western slope of Great Blue Hill, a distance of 58,520 feet, or a little more than 11 miles from the observatory. In the direction of the meridian

it proved necessary to purchase the privilege of tunneling a neighboring building in order to obtain a clear view of the mark. The stone pier served its purpose admirably, but it has now disappeared.

Two small rooms were constructed to the west of the transit instrument for the continuance of the observations of magnetic declination which Bond had been making for some time at his Dorchester observatory. Another building was placed to the north of the transit instrument for the use of the Lloyd magnetic apparatus provided by a grant of the American Academy of Arts and Sciences. These magnetic observations were made under a cooperative plan proposed by the Royal Society of London. The apparatus consisted of three magnetometers, one for declination, one for horizontal force, and one for vertical force. The details of the arrangements may be found in the Annals of the Observatory.[1]

During the years 1840 to 1842, Bond continued the observations begun at Dorchester in connection with the geodetic work carried on by the Government of the United States. Aside from this, the work of the Observatory was chiefly magnetic and meteorological. The magnetic observations, made in cooperation with other observatories in different parts of the world, were carried on for three years, but they proved to be extremely engrossing and interfered seriously with any attempt to initiate new astronomical observations. Furthermore, the equipment was unsuitable for astronomical investigations. Bond was assisted in the execution of his plans by his sons, William C. Bond, Jr., and George P. Bond, and also by an organization of students styling themselves "The Meteorological Society of Harvard University." No salary was paid either to Bond or to his assistants. Joseph Lovering, Hollis Professor of Mathematics and Natural Philosophy, and Benjamin Peirce, Perkins Professor of Mathematics and Natural Philosophy, both took a deep interest in the beginnings of the Observatory.

[1] H. A., 1, vi–xiv, 1856.

The Naming of the Observatory.—No definite name was chosen for the Observatory for a number of years, although several were proposed. It was even suggested at one time that the institution, which after its foundation was usually referred to as "The Observatory at Cambridge," should bear the name of some hoped-for benefactor, who might suitably endow it. There can be no doubt, however, that its founders intended it to be associated with Harvard University.

The Observatory has long been popularly known as "The Harvard College Observatory," or simply as the "Harvard Observatory." An observatory is usually understood to be an astronomical institution, but the existence of a meteorological observatory as a department of Harvard University makes desirable the use of the prefix "Astronomical." The Statutes passed in 1849 declare that the name shall be "The Astronomical Observatory of Harvard College"—still the official title, although, since 1780, Harvard has held the rank of a university.

In their report for 1851, the Visiting Committee, including such distinguished men as Josiah Quincy, William Mitchell, Robert T. Paine, David Sears, J. Ingersoll Bowditch, and Francis Peabody, proposed that the name be modified by changing the word "College" to "University":

> To an Observatory which has, from the nature of its objects and duties, a necessity of frequent intercourse with foreign seminaries, it is far from unimportant that the most comprehensive name, and that by which it is best known in Europe, should be retained. Your committee, therefore, respectfully suggest, if it shall not be deemed advisable that the Observatory should be hereafter, as it has been heretofore, designated by the name of the city in which it is located, that it be permitted to take the name of The Observatory of Harvard University.

No attention seems to have been paid to the proposal. Although the Observatory is in reality a department of Harvard University, the retention of the word "College" in its name appears to be consistent with the official name of the Corporation of Harvard University—"The President and Fellows of Harvard College."

Standing of the Observatory in the University.—The relations between the College professors and the newly appointed "Astronomical Observer" were for several years ill defined and uncertain, as may be inferred from numerous letters written by persons of influence, as well as by acts of the Corporation. In 1839, in the official report of the agreement with Bond by action of the Corporation, it is stated that the southwest room of the Dana House is reserved

> . . . as an observer's room, to be used in common by the said Mr. Bond and the Professor of Natural Philosophy for the time being in Cambridge, and the chamber over the same, together with the small room adjoining, for the exclusive use of said professor.

Sometimes the name of the professor preceded that of Bond. For example, President Quincy, in 1840, referring to the use of the magnetic instruments given by the American Academy, wrote: "And placed the whole at the disposal of Professor Lovering and Mr. Bond."

Such an arrangement evidently gave opportunity for friction, but no complaint seems to have been made by Mr. Bond, one of the most unassuming of men. The uncertainty was still present in 1845, when the site of the new Observatory was about to be occupied. This is apparent from a letter addressed to President Quincy by John Quincy Adams containing various recommendations for improving the efficiency of the Observatory:

> 4th. The appointment of an Observer and one Assistant, a measure indispensable to make the whole establishment effective for the purpose of continuous observation. In the first instance, it is very important and desirable that these offices should be conferred upon Mr. Bond and his son, but as a permanent institution, it seems that provision should be made for a regular succession to these offices. That the mode of their appointment, the occasions of vacancy, the tenure of their offices, their right of occupation and custody of the buildings, both dwelling house and Observatory, and of the adjoining grounds, should be regulated and prescribed. That the line of division between the duties of the Observer, and those of the Perkins Professor of Astronomy and the Mathematics, should be accurately drawn. That the extent to which the

Professor shall have a right to the use of the instruments and of access to the Observatory, for the purposes of instruction in his department to the students of the University, should be clearly defined. Whether some liberty of occasionally assisting the Observer in making observations may be indulged to students, whose inclinations may take a special direction to the study of physical astronomy, and whether the teaching of the use of the instruments to all students of the higher classes may not be included among the joint duties of the Professor and the Observer.

Mr. Adams foresaw clearly the problems which would arise later. In 1849, the Statutes of the Observatory were passed, which use the term "Director," in place of "Astronomical Observer," and give to him entire authority over the details of the Observatory equipment and work, subject only to the authority of the governing boards of the University The Observatory was thus wisely made a distinct department of the University, with research as its chief duty.

The Observatory and the Public.—The policy of the Observatory in regard to teaching and service to the public has varied greatly from time to time, under different directors and presidents of the University. Perhaps the suggestions of Mr. Adams represent a wise and conservative course of action. As chairman of the Visiting Committee in 1847, he advised in his report that a plan be provided:

For the occupation and employment of the Observatory in both its capacities as a constituent department of the University, for the instruction of youth and as one of the towers of human science erected by a spontaneous and sympathetic consent of civilized nations, to extend by constant observation and calculation the knowledge of the physical universe.

For many years after the installation of the "Great Telescope,"[2] much time and effort were expended in entertaining the public. The popular demand for the privilege of using the telescopes has always been much greater than the Observatory could satisfy without too great interference with its scientific work. All concessions of this sort have reduced the

[2] See p. 26.

scientific output of the members of the staff, and sharp restrictions have unfortunately been necessary. The problem could best be solved by a special endowment for the teaching and entertainment of the public, which would thus be carried on more satisfactorily, and without interfering with the scientific work of the Observatory. Such a plan was first proposed by George P. Bond, second director of the Observatory, in 1860, and the need of some arrangement of the kind has been generally recognized ever since.

In recent years, under the direction of Dr. Shapley, a closer cooperation has been effected with the teaching staff of the University, and the opportunities for advanced astronomical study have been much extended. A series of "open nights" has also been introduced at the Observatory, for which tickets are distributed, in the order of application, to the public. On these nights visitors have the opportunity to observe some celestial object or objects in the telescope, to see the illuminated photographs of stars, nebulae, comets, and other objects, and to listen to brief lectures on astronomical subjects. The Observatory has also given much assistance to the American Association of Variable Star Observers and to the Bond Astronomical Club, societies largely composed of amateur scientists and the scientifically interested public.

CHAPTER III

GROWTH OF THE PRESENT OBSERVATORY

It was clear to the founders of the Dana House Observatory that the equipment and arrangements were of a provisional nature. The institution was ill equipped, and work was carried on entirely by volunteer observers; but the University then had no further available funds. If the Observatory was to take a position at all in keeping with the spirit of its founders and the traditions of Massachusetts and the University, some great impulse was needed to arouse the public interest. Otherwise, like most of the other observatories founded at about the same time in different parts of the United States, though it might enter upon its task with enthusiasm, it would rapidly sink as a center for astronomical research, into a condition of comparative uselessness.

Endowment of the New Observatory.—The heavens themselves furnished the inspiration that quickened the public interest. In March, 1843, a comet of surpassing size and splendor appeared, and attracted intense interest. Appeals were made to the "Observatory at Cambridge" for observations and information. Unfortunately (or perhaps fortunately) the Observatory could not satisfy the demand, for it possessed no instrument with which positions of the comet could be accurately determined. Inspired by the remarkable celestial phenomenon, and impressed by the inadequacy of the equipment at the Observatory, a few men held a meeting in Boston at the office of Mr. J. I. Bowditch, always a friend of the Observatory, to consider means of providing new instru-

meeting of citizens in order to discuss a plan for obtaining for the Observatory an equatorially mounted telescope of the highest quality. This gathering took place at the rooms of the Boston Marine Society, and was attended by many men of scientific interests and abundant means. Abbott Lawrence acted as Chairman, and John Pickering, Professor Peirce, William Appleton, and S. A. Eliot made addresses. A committee was formed to obtain subscriptions, and another committee, to prepare a report. At this meeting, also, David Sears, through President Quincy, indicated his wish to give $5000 for the erection of a tower for the reception of a telescope, provided others would subscribe $20,000 for the purchase of the telescope. This proposal was referred to as "munificent," and indeed it *was* munificent in comparison with what had already been given to the Observatory; also, when the standards of that day are taken into consideration, the sum proposed was really large. Materials and labor were then vastly cheaper than now; and the salary of the leading professors at the University was from $1500 to $1800 a year. In the College catalogue for 1839 to 1840, the estimated necessary expenses of a student for the college year at Harvard, including tuition, fees, books, room, and board, were placed at $195.

The $20,000 needed to make good the $5000 offered by Mr. Sears was promptly contributed by citizens of Boston, Salem, New Bedford, and Nantucket. No restrictions of any kind were imposed upon the gifts; the telescope, when obtained, was to be devoted to the best interests of astronomy. The amount subscribed was sufficient to obtain the best telescope which could be bought at that time; and it only remained to select a desirable form of instrument and the best maker.

Between a refracting and a reflecting telescope, the choice was wisely made in favor of the former. The reflecting telescopes of that day were much inferior to the refractors both in definition and in convenience of manipulation. An equatorial form of mounting was also chosen, such as had been found extremely satisfactory for the refracting telescopes

already in operation at the Dorpat and Poulkova Observatories. After consultation with astronomers and opticians in various countries, the contract was awarded to Merz and Mahler of Munich, the successors of Fraunhofer. By the terms of the contract, two lenses were to be made of 15 inches aperture, of a quality equal to that of the lens recently made for the Poulkova Observatory. A choice was to be made of one of these, with the privilege of rejecting both, should the quality be considered unsatisfactory.

The Observatory Transferred to the Present Site.— It had been recognized for some time that the Dana House location was unsuitable for an observatory of the first class, such as was now contemplated. After a careful investigation, a new site was found which promised to be satisfactory. It was a part of the Craigie estate, known at the time as "Summer-house hill," and without doubt it was the best site in the vicinity of the University. The highest part rises about 50 feet above the neighboring lands, and is 80 feet above tidewater. At that time the Craigie estate was for the most part open country; and with no electric lights and no street cars or heavy trucks, the situation was as favorable as could be desired. The immense growth of Boston and Cambridge, which after three quarters of a century has again made the surroundings of the Observatory very unfavorable for astronomical observations, could hardly have been foreseen.

Fortunately the University was able to purchase a sufficiently large area in the most desirable location. The land originally acquired for the Observatory, and set aside for its use, was between six and seven acres in area, and was bought at a cost of $4100.

In a report by the Treasurer of the University for 1845 to 1846, it is stated that:

The Observatory account stands charged with a balance of more than nine thousand dollars against it. Of this about six thousand and five hundred dollars have been spent on the buildings and grounds. A

further sum remains to be paid on account of the dome, which is not yet completed; and thirteen thousand and five hundred dollars are to be expended on the large telescope, and a transit circle which has been ordered from London. So that on the whole, the College will have spent on the Observatory nearly double the sum that it has received.

The whole expense up to this time had been about $50,000.

The observer's house and a considerable part of the Observatory buildings had been completed by September, 1844, and the instruments were removed from the Dana House site to their new positions. The 4-foot transit instrument and the small out-buildings occupied by the magnetic apparatus were removed to a location about 60 feet north of the new main building. The following winter, a transit instrument made by Troughton and Simms and imported by the Government of the United States was mounted in the prime vertical and was employed in observing the zenith distances of stars for the determination of the latitude of the new Observatory, according to the method of Bessel. The use of this instrument was granted by Lieutenant-Colonel James D. Graham, of the Northeastern Boundary Commission of the United States.

A small refractor was mounted on the grounds in December, 1844. It was replaced later by one somewhat larger. With these telescopes observations were made, during 1845 and 1846, of eclipses, comets, and sunspots.

Installation of the 15-inch Refractor.—In May, 1846, Messrs. Simms and Cranch, the London agents appointed for the purpose, visited Munich and made an examination of the two lenses for the large refractor, which were then ready for inspection. They found one of the lenses of better quality than the other, and apparently satisfactory in every respect. The tests which were applied are described in full in Harvard Annals, 1, cix. They were the best which the agents could make under the circumstances, which, however, did not permit an examination of any celestial object. The better lens was accordingly accepted and forwarded to Cambridge. Its quality proved to be excellent. After more than three quarters

of a century, during which the building and mounting have become somewhat antiquated, the lens itself remains in splendid condition. This excellent performance constitutes a tribute not only to the makers, but also to the long line of observers who have used and cared for the lens during many years.

The object glass of the "Great Refractor" was received at Cambridge on June 11, 1847, and on June 23 and 24 it was placed in its proper position, the mounting having already been prepared for it in the Sears Tower. One can readily imagine with what interest and even anxiety it was first turned toward the sky. Added to some uncertainty as to the perfection of the lens and its equipment was the fact that the public regarded the telescope as the most efficient in the world and expected notable observations and discoveries through its use. The first objects examined were the Great Nebula in Andromeda and the Orion Nebula. The results of these and many other tests were most satisfactory. Public expectations were soon satisfied by the discovery of the inner dark ring of Saturn, known as "Bond's Ring," and by other striking observations, some of which are described in later chapters.

Additions to the Equipment.—Next in importance to the large refractor, in the equipment of the new Observatory, was a transit circle, made by Mr. Simms, of Troughton and Simms, of London. This instrument was received in 1848 and was mounted in the east wing. It had a circle 4 feet in diameter, and an objective, 4¼ inches in diameter and 5 feet in focal length. It appeared to be as perfect an instrument as could be obtained in those days; but an injury, which apparently was received during its shipment from London, affected the divisions of both circles, and prevented its use for the measurement of absolute declinations. It was used, however, for many years, as a transit instrument, for the observations of time-stars, and for the determination of right ascensions.

The west wing of the Observatory was designed for the use of a transit instrument, and also contained a small dome

for a refractor of moderate size, rooms to meet the needs of computors, and the library. This wing was not finished until 1851.

A comet-seeker, presented by Mr. J. I. Bowditch, proved a valuable addition to the equipment. With it, George P. Bond discovered independently 10 comets, although it later appeared that most of them had been seen earlier in Europe. This was before the establishment of telegraphic communication between Europe and America.

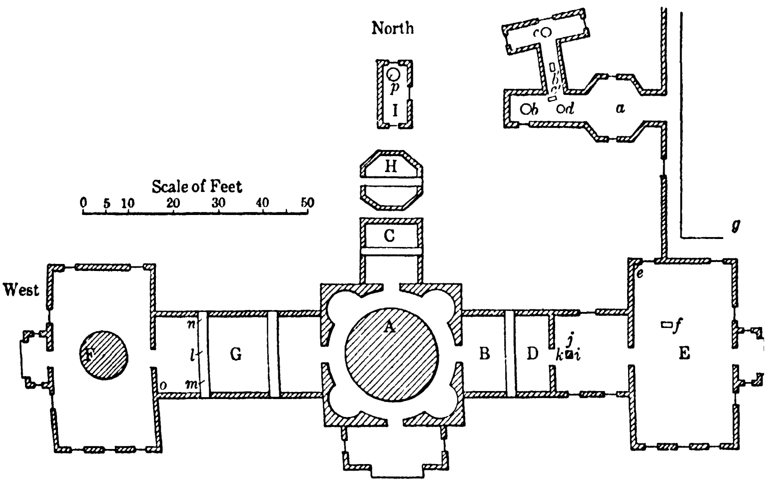

FIGURE I.

Plan of the buildings and instruments of the Harvard Observatory as given by William C. Bond in the first volume of the Annals, 1856.

The appearance of the completed main building of the new Observatory is shown in the illustration on the frontispiece, taken from a woodcut which appeared in the Boston Transcript in 1852. The view is from the southeast, near the corner of Concord Avenue and Bond Street. The general plan of the buildings and instruments is given in Figure 1 taken from the first volume of the Annals. The director's residence was at E, the recently acquired transit circle at B, the prime-vertical transit at C, the old transit circle at *l*, and the small equatorial at F. Minor instruments were placed in various positions in

the main building, or in small isolated shelters. At the center of the plan, at A, in the Sears Tower, was, and still remains, the large refractor.

Many details of the installation of the Observatory are given by William Cranch Bond in Volume 1 of the Annals of the Observatory. It seems unnecessary in this place to give more than a brief summary of them. Although much work was done with other instruments, the real interest of the public and of the astronomers was associated with the large equatorial telescope. The dome containing it is still the central and striking feature of the buildings. The Sears Tower is 32 feet square, with solid foundations and walls. These are square on the outside, but are brought into a circular form within, on the first floor, with recessed corners. The pier occupies the center of this room, generally referred to as the "Rotunda." In recent times the pier has been surrounded by book shelves. In the dome room above are recesses similar to those below, and on the north, east, and west sides of the dome, doors open upon iron balconies which have proved very useful for miscellaneous observations. The dome itself, a hemisphere in form, is 30 feet in diameter, and rests on spherical iron balls freely moving in grooves both above and below. By means of suitable mechanical contrivances the dome, which weighs 14 tons, can be revolved by one person through an entire circuit in about half a minute. A suitable opening was provided, extending from three degrees beyond the zenith to three degrees below the horizon, and covered with an arrangement of movable shutters.

The telescope was mounted on a pier of most substantial workmanship, after the usual methods of Bond. The foundation was placed 26 feet below the natural surface of the ground. Upon a cement base, the pier was constructed of large blocks of Quincy granite. It was made entirely solid to the height of 11 feet above the foundation. The floor of the dome is reached at the height of 33 feet, where the pier is surmounted by a circular granite capstone, 10 feet in diameter and 22 inches

in thickness. Upon this stone rests a granite pedestal, weighing 11 tons, to the top of which the bedplate of the equatorial mounting is secured. The pedestal is referred to by Bond as a "tripod," from the fact that it was constructed to rest on the capstone by three bearings, so situated in regard to the center of gravity of the whole block and telescope that each bearing supported a nearly equal share of the weight. This was a favorite method of Bond, who used it in all his piers. The bearings were rounded protuberances. This method gave the utmost steadiness, and permitted an easy change of position for adjustment of the telescope.

In the equipment of the dome and telescope, Bond not only made use of all the information which he had obtained abroad at various European observatories, but brought to the problems his own original ideas, derived from many years of practical work. Everything was carried out with his characteristic thoroughness and mechanical skill, as is shown by the observing chair for the large refractor, which was constructed under his direction. Seated in a comfortable chair, the observer, by the rotation of an adjacent wheel, can elevate or lower himself to any desired altitude. The position of the observer in azimuth can be arranged at will by means of a circular track on which the whole apparatus revolves. This observing chair, although somewhat cumbersome and out of date, has served its purpose well, and is still in use. So admirable was its construction that it gives no evidence of being worn out after many years of active service.

The Phillips Bequest.—With the opening of the new Observatory, the question of salaries for the observers became urgent. Until 1846, no salaries were paid. It was obvious that such a system could not long continue. Since the University had no funds for the purpose, provision was made for two years through the generosity of a few citizens of Boston.

In 1849, by the will of Edward Bromfield Phillips, the sum of $100,000 was received by the Observatory. This was a

munificent bequest for that time. It opened up new possibilities, and obviated much hardship and worry. Perhaps, however, too much was expected from it. Section VII of the Statutes of the Observatory states:

> The salaries of the Director and Assistants shall be fixed by the President and Fellows, and be paid out of the income of the fund established for this object by the will of the late Edward Bromfield Phillips. From the income of the same fund shall be drawn such sums as, in the judgment of the President and Fellows, shall be necessary or expedient for the purchase of books and instruments, and for their repairs and preservation.

For some years after the enactment of the Statutes, this Fund may have been able to supply the demands made upon it, but later it was obviously insufficient to care for the great growth of staff and equipment. Further endowments, however, supplied other resources, and relieved the strain on the Phillips Fund.

The Cambridge Astronomical Society.—The growth of astronomical institutions on the American Continent ran parallel to the development of the science in Europe. The Royal Astronomical Society, founded in 1820, had held monthly meetings since its foundation. In 1854 the first forerunner of the American Astronomical Society was founded at Cambridge. The leading spirit in its foundation appears to have been Benjamin Peirce, at the time Perkins Professor of Astronomy and Mathematics and head of the theoretical department of the American Ephemeris and Nautical Almanac, then located at Cambridge. Professor Peirce thought the Society should be formed as a local body, but in such a way that it might later become a branch of a national astronomical society, the foundation of which he foresaw. The original records of the recording secretary of the "Cambridge Branch of the American Astronomical Society" are in the possession of the Harvard Observatory.

The members of the Society were very carefully selected, and the papers and discussions at the meetings were highly technical. The sciences to be covered by the members of the

Society were astronomy, geodesy, and mathematics. Profess(Peirce was chosen first President. Joseph Winlock, at the tin a computer in the office of the American Ephemeris, was ma(Recording Secretary, and John D. Runkle, Correspondir Secretary. Other distinguished members of the Society wer Newcomb, Gould, George P. Bond, Hill, Oliver, Peters, Eas wood, Kerr, Wright, and Safford.

Meetings were held each fortnight. The first took place c January 24, 1854, and others followed with considerab regularity until October 24, of the same year, when the seve teenth meeting occurred. The eighteenth, and, by the record the last meeting ever held, took place on September 22, 185

The American Astronomical Society, first known as tl "Astronomical and Astrophysical Society of America," tl establishment of which was predicted by Peirce in 1854, w begun in 1898, at a meeting of astronomers held at the Harva Observatory.

The First Directors; William and George Bond.– William Cranch Bond, the first director of the Observator and the first to hold the Phillips Professorship of Astronom died in 1859, at the age of seventy years. He had been i charge of the Observatory for about 20 years. The Universit could have made no wiser choice of a leader for the establishmer of the institution and for its control and encouragement durin its early years.

On the death of William Cranch Bond, his son, George Philli Bond, was his logical successor. Even when a young boy h had assisted his father in his observations, and in the work (the new Observatory he had taken the leading part. H familiarity with the needs and the activities of the institutio the abilities which he had already shown, and the scientifi reputation which he had gained, made him the choice of th Corporation, and he was appointed second director of th Observatory, and Phillips Professor of Astronomy, in 185(The only other candidate for the position appears to have bee

Professor Benjamin Peirce, no doubt the ablest American mathematical astronomer of his day, but with little or no experience in observational astronomy. George P. Bond gave a whole-hearted devotion to the interests of the Observatory. Unfortunately, his health slowly failed, and he died in 1865, at the early age of thirty-nine years.

Under the Bonds, whose lives and achievements are described elsewhere in this volume, the Observatory gained an enviable international reputation. The large refractor was kept constantly busy in the observation of Saturn, Mars, and other members of the solar system, of Donati's and other comets, of the great nebula in Orion, and of other celestial objects. The positions of faint stars were determined in a zone extending from the equator to 1° 00′, north declination. Much attention was given, through the voluntary aid of Messrs. Whipple and Black, of Boston, to a study of the application of photography to scientific research; and George P. Bond, especially, clearly foresaw the amazing possibilities of the introduction of photographic methods into astronomical investigation. During all this time, in spite of the income of the Phillips Fund, the want of money for badly needed developments was always keenly felt. Assistants came and went, drawn by their interest in astronomy and the reputation of the Observatory, and driven away by their inability to exist on the salaries offered.

A year elapsed after the death of George P. Bond before the appointment of his successor. During this interval, the Observatory was in charge of Professor Truman H. Safford, who applied himself chiefly to the preparation for the press of additional volumes of the Annals. A large amount of unpublished material had accumulated, and its reduction and publication were carried forward as rapidly as the limited staff and inadequate income permitted.

Appointment of Joseph Winlock.—Joseph Winlock, the third director of the Observatory, began his term of service in 1866, at the age of forty years. He had received adequate

training, and had gained a wide experience in mathematica and astronomical lines. He had held the positions of Professo of Mathematics and Astronomy at Shelby College, Head of th Mathematical Department of the United States Naval Academ at Annapolis, and member of the United States Naval Observa tory at Washington. His interests lay especially in what ha been known as the "old astronomy," or the astronomy o position. His skill in mechanical appliances of all kinds wa unusual, and his energies were directed largely toward th perfection of the equipment of the Observatory. Not satisfie with the transit circle already in use, he arranged for the pur chase of a new meridian instrument of larger size and greate perfection. With this new instrument William A. Roger began work on one of the zones of the international cooperativ revision of the Durchmusterung, that between 50° and 55° o northern declination.

Much effort was expended during Winlock's administratio in the perfection of the time service, which furnished accurat time for the people of Boston and vicinity. This service wa made to provide a small but much needed addition to th income of the Observatory. The large refractor was devote especially to physical researches, and to the measurement o binary stars. It was also employed in an unsuccessful searc for new planets, and for the determination of positions o asteroids and comets. Various spectroscopic studies of stars of nebulae and comets, of the aurora, and especially of th sun at the total eclipses of 1869 and 1870, were undertaken

During this period Professor Shaler of Harvard began a investigation of the lunar surface, with the large refractor from the viewpoint of a geologist. Trouvelot also used th same instrument for several years in obtaining numerou drawings of various celestial objects. Meteorological observa tions were regularly made.

Professor Winlock's activities were suddenly and unex pectedly closed by his death at the age of forty-nine year in June, 1875.

Development of the Observatory under Pickering.— Edward C. Pickering, the fourth director of the Observatory, received his appointment in 1876, but he did not assume his new duties until February 1, 1877. During the interval, Professor Arthur Searle was acting director of the Observatory, and devoted the energies of the small staff to the preparation for the press of several volumes of the Annals, in addition to the usual astronomical observations.

Mr. Searle brought up to date the history of the Observatory, begun by William C. Bond in the first volume of the Annals, publishing this work in the eighth volume and including elaborate diagrams of the Observatory grounds and buildings, the various instruments, their piers, and the electrical connections, as well as the different clocks and chronographs.[1]

In 1877, at the beginning of Pickering's administration, the condition of the Observatory was that of an institution struggling with insufficient income to support its staff, and to find means for the publication of the accumulated observations of preceding years. It is significant of his methods that once he had begun work with the facilities already provided, Pickering made repeated efforts to increase the income. He found the Observatory equipped with two instruments of the highest class for that time: the large equatorial refractor, and the new meridian circle obtained by Winlock. It was extremely desirable that these instruments should be fully employed, and at the same time that the results of the observations should be prepared promptly for publication. Up to that time, only the first eight volumes of the Annals had been published, with the exception of Volume 4, Part 2, which was nearing completion by Professor Safford, then at Williams College. By the close of Pickering's directorship, the number of published volumes of the Annals was approaching one hundred.

As a physicist, Pickering naturally directed the work of the Observatory largely into astrophysical lines. Nevertheless, the work of the large meridian circle occupied the time

[1] H. A., 8, Part 1, 1877.

of one or more assistants and a corps of computers for nearly 40 years.

During Pickering's term of service, the endowment and equipment of the Observatory were greatly increased. His leading interest for many years was in the photometry of the stars. At first, this was confined to visual observations, but later became more and more photographic. A rare opportunity for spectroscopic researches was also utilized to the utmost, chiefly by photographic methods. Toward the close of his life, the completion of the Henry Draper Catalogue of stellar spectra, the classification for which was done by Miss Cannon, absorbed his attention. This catalogue, consisting of nine volumes of the Annals, was nearly finished at the time of his death. The photometric and spectroscopic researches of Pickering's time are described in later chapters.

Some of the other problems which had a great development during the directorship of Pickering were the discovery and study of variable stars, novae, clusters, and nebulae, as well as observations of comets and planets. The creation of the library of celestial photographs, mainly of stars, containing more than 200,000 original negatives, was a unique achievement, involving the foundation of the most valuable and irreplaceable astronomical collection in the world.

In order to extend the researches to the whole sky, an auxiliary southern station was established in 1890, under the Boyden Fund, at Arequipa, Peru. This station remained in active operation until the end of 1926, when it was removed to Mazelspoort, near Bloemfontein, South Africa.

Professor Pickering died on the third day of February, 1919, at the age of seventy-two years. He was Director of the Observatory for 42 years, more than one half of the time since its foundation in 1839.

During nearly three years following, the Observatory was in charge of Professor Solon I. Bailey, whose chief endeavor was to push forward as rapidly as possible the unfinished researches begun during Mr. Pickering's administration. The

staff at this time was large and able, and considerable progress was made.

Shapley Chosen Director.—The fifth and present director of the Harvard Observatory is Harlow Shapley. He was graduated from the University of Missouri in 1910, and took the degree of Doctor of Philosophy from Princeton University in 1913. While at Princeton, he was the author of an important series of studies of eclipsing binaries. Called to the Mount Wilson Observatory in 1914, he soon gained an international reputation, especially from his researches on Cepheid variable stars and globular clusters, and their relation to the structure and size of the galactic system.

In November, 1921, Dr. Shapley was chosen by the Corporation of Harvard University as the fifth director of the Observatory. In command of the great accumulations of data at Harvard, he has extended his investigations so as to include many additional lines of observation and discussion, which may be expected to throw light on the nature, distribution, and motions of the different members of the visible universe.

CHAPTER IV

INSTRUMENTAL EQUIPMENT

THE development of modern astronomy has been intimately associated with the invention and perfection of mechanical aids. Without the telescope, the spectroscope, and other astronomical instruments, comparatively small advance would have been possible.

A large number of telescopes and various other instruments have been in use at the Observatory during its history. A list of telescopes is given at the end of the chapter; a brief description follows of the most important instruments, special attention being given to those which have peculiarities in construction devised by members of the Observatory staff. No attempt is made to explain the principles and construction of standard instruments.

The Chronograph.—The introduction of a satisfactory astronomical chronograph, for recording observations made with the meridian circle and other instruments, marked an important advance in observational procedure. Its use soon became almost universal in time observations for geodetic work, as well as in more purely astronomical investigations. The credit for the invention and perfection of a successful chronograph was for a long time the subject of much controversy. As usual in such cases the instrument was the result of many attempts by many minds. As developed by the Bonds, it was called by them the "spring-governor and electric clock." The term "spring-governor" refers to the control mechanism, and the electric current, which had recently come into use, was a necessary element in its operation.

The first experiment for the determination of differences in longitude by the electric telegraph appears to have been made

r Admiral Wilkes in 1844. Electric signals were used which ere recognized by the ear. Later, similar attempts were ade in various places until the method became standardized. he idea of an automatic current-interrupter occurred to W. C. ond early in 1848, according to his son, G. P. Bond. The ea probably presented itself to others at about the same time, ice in the same year O. M. Mitchel, at the suggestion of alker, of the United States Coast Survey, constructed such apparatus. Various improvements were suggested by hers. Lack of uniformity in the revolution of the cylinder which the recording sheets were placed was the outstanding fficulty. The Bonds, by the invention of the spring-governor, viated this difficulty. They constructed an instrument in 50 which was the first really satisfactory astronomical chrono- aph. It was due to the efforts of W. C. Bond and his two ns, Richard and George. It received the award of a gold edal at the Crystal Palace Exposition in England and soon me into general use, replacing the old eye and ear methods. In the Bond chronograph a sheet of paper is placed on a linder which makes a complete revolution once a minute. n the paper rests a pen, which is electrically connected with a andard clock, and is drawn slowly in an axial direction along e cylinder. By means of automatic signals, the pen makes ch second a slight movement to one side. Time intervals ve thus been converted into space intervals. The distance tween the successive second marks may be a centimeter, or ore, a quantity readily divisible into hundredths. The cord of the star's transit across the wires of a reticle is made an observer, who presses the key in the same electric circuit ting on the pen. The sheet may be filed and discussed at y time.[1]

The 15-inch Visual Refractor.—This instrument played e chief rôle in the early years of the Observatory. It has achromatic lens of the usual form, consisting of crown and

[1] H. A., 1, Part 1, xlix, clviii, 1856.

flint glasses. The lens and mounting were constructed by Merz and Mahler of Munich, Bavaria, the successors of Fraunhofer. The lens has an effective aperture of 15 inches and a focal length of 22½ feet. The granite pier on which it was mounted is constructed in the thorough and massive way characteristic of the director, W. C. Bond. The mounting is of the German equatorial form. The polar and declination axes are of steel, and the telescope tube, of light wood and paper strengthened by iron diaphragms. The exterior of the tube was veneered with mahogany. Eighteen eyepieces were provided, furnishing powers of from 100 to 2000 diameters. The lens, the work of Merz, proved to be a most admirable one. Certain features of the mounting, however, were found unsatisfactory. Bond states that:

> The arrangements of the divisions of both the declination and hour circles are awkward, and the reading off of both attended with needless trouble; the screw for adjusting the focus of the eye-pieces is inconveniently situated; and the clock for regulating the movement of the telescope is disproportional to the other parts of the instrument, and too feeble, rendering it in cold weather nearly useless.[2]

These faults were in large part corrected later by the Clarks, who introduced changes and improvements which brought the mounting and clockwork up to the standards of that time.

The 15-inch telescope, unsurpassed in its day, was installed at the Observatory in 1847, as already described. Around it cluster most of the tradition and sentiment of the early days of the Observatory. It was affectionately referred to as the "Great Telescope." Bond called it "our incomparable telescope." Great things were expected of it by its donors—new discoveries and improved views of known objects. Nor was this expectation disappointed, although few spectacular discoveries were made. For half a century it held its position as the principal instrument of the Observatory until its importance waned with the introduction of photographic instruments. Although photographic work had been early undertaken with

[2] *Ibid.*, xxxi.

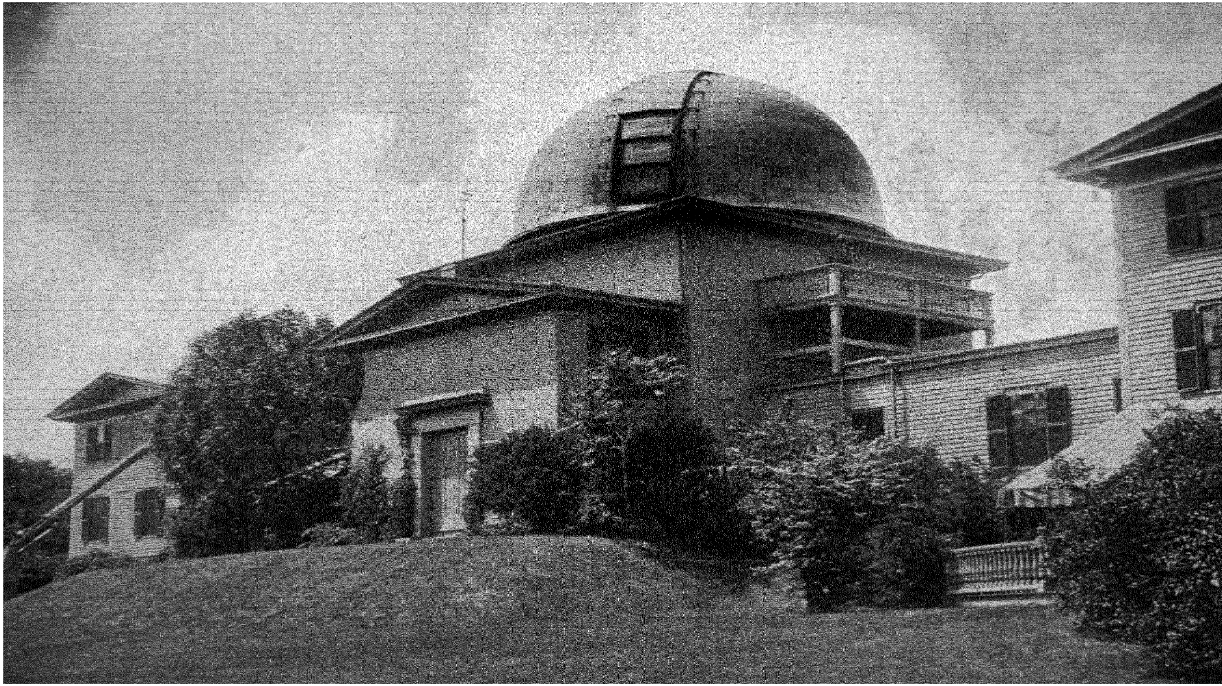

PLATE III.—THE DOME OF THE 15-INCH REFRACTOR FROM THE SOUTH-EAST.

(Facing page 40)

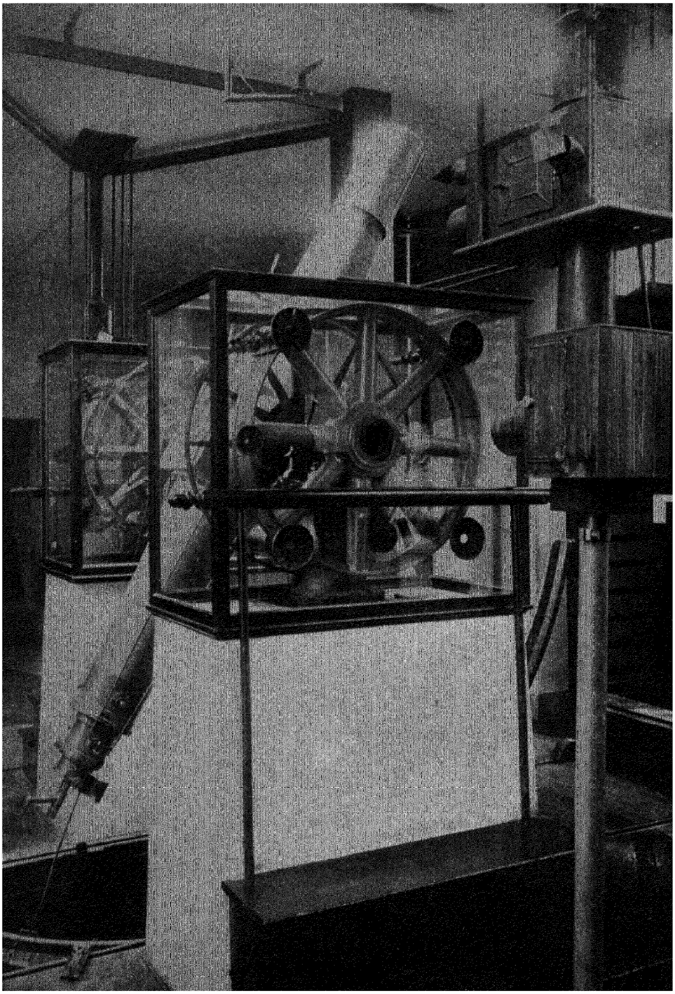

Plate IV.—The Meridian Circle.

this telescope by the Bonds, the lens, corrected only for the visual rays, gave poor photographic definition, and the results are to be regarded merely as experimental and exploratory.

Transit Instruments.—The astronomical equipment of the old Observatory at the Dana House, within the College grounds, was largely the property of W. C. Bond, and included a small transit instrument. For the new Observatory, a Troughton and Simms transit circle was provided, as described in the preceding chapter.

One of the chief concerns of Joseph Winlock, when he became Director of the Observatory in 1866, was the acquisition of a new meridian circle of the best class. After elaborate investigations at home and abroad, Winlock ordered a new instrument from Troughton and Simms, the lenses for which, however, were made by Alvan Clark and Sons. This meridian circle had an object glass 8¼ inches in diameter and of more than 9 feet focal length. The diameter of each of the graduated circles was 3 feet. The collimating lenses were 8 inches in diameter. Various modifications were introduced into this instrument by the makers at Winlock's suggestion. The most important of these were the shortening of the piers and the relieving of undue pressure on the pivot bearings by a system of levers with friction rollers. Stability was thus gained and the graduated circles were brought entirely above the piers, which were covered with glass cases as a protection against dust.

This large meridian instrument was not received and mounted until 1870. It was placed in the west wing and for many years thereafter was one of the most important instruments of the Observatory. The observations of the Zone of the Astronomische Gesellschaft, from $+49^\circ\ 50'$ to $+55^\circ\ 10'$, by Rogers, and that from $-9^\circ\ 50'$ to $-14^\circ\ 10'$ declination, by Searle, were all carried out with this instrument as described elsewhere.

Another meridian instrument of special interest was the "Russian transit," or "broken transit," made by Herbst, mechanician of the Poulkova Observatory, under the direction

of Struve. It also was received in 1870, and was mounted just west of the large meridian circle. It was a portable instrument having a lens of 2¾ inches diameter and 33 inches focal length. A prism placed at the middle of the axis reflected the light to the eyepiece at one side. The instrument was used for longitude determinations and other occasional observations, and for teaching.[3]

The Photographic Doublets.—Edward C. Pickering, with the aid of William H. Pickering, began experiments in celestial photography in 1882. The advantages of the doublet were early recognized, and a long series of doublets of different sizes have contributed much toward the results obtained at the Observatory during the last 40 years. Among the most useful of these instruments have been the 8-inch Bache, the 8-inch Draper, the 16-inch Metcalf, and the 24-inch Bruce. The donor's name has generally been used to designate these telescopes. All four are of similar construction. The 8-inch Bache lens was originally a Voigtländer portrait lens. It was bought at secondhand and refigured by the Clarks. Each combination of the doublet consists of a crown and a flint glass. The refiguring of the lens was necessary not only to improve the definition but to change slightly the focal length, making it 114.6 centimeters, so that the scale of the photographs became 2 cm = 1°, the scale of the Durchmusterung charts.

When the Bache telescope was sent to Peru in 1889, for work on the southern sky, it was replaced at Cambridge by another similar instrument called the "Draper 8-inch doublet." Objective prisms were employed with both instruments for obtaining photographs of stellar spectra. Supplemented by the work of larger instruments, they have led to the discovery of numerous novae, variables, asteroids, and nebulae, and have provided many of the photographs involved in the Draper Catalogues of stellar spectra.

[3] An elaborate description of the buildings and equipment of the Observatory from 1855 to 1876 was given by Searle in the Annals (**8**, Part 1, 1876).

In 1890, Miss C. W. Bruce of New York gave the Observatory \$50,000 toward the construction and maintenance of a large photographic telescope. Telescopes with a single achromatic lens, corrected for photographic light, were used at that time for photographic work at nearly all observatories. The field of good definition of such a telescope is comparatively small. A doublet gives good definition over a region several times as great. For any research, therefore, such as the charting of stars, nebulae, and other celestial objects, much greater speed is possible with a doublet than with a telescope of the usual form, such as that constructed by the Henry Brothers for the use of the Astrophotographic Congress. On this account Pickering decided to use the Bruce gift for the construction of a much larger doublet than had hitherto been made. The result was the 24-inch Bruce telescope of 11 feet focal length. In effect it was an enlarged 8-inch Bache. The scale of the resulting photograph was 1 mm = 1′, or 6 cm = 1°.

The construction of the Bruce telescope was intrusted to Alvan Clark and Sons, of Cambridgeport. It was completed in 1894 and after preliminary trials at Cambridge, was sent to the southern station of the Observatory at Arequipa, Peru, where it remained until the closing of that station in 1927. It has proved to be of immense value in the work of the Observatory. The mounting was originally of the open fork type, the telescope tube being suspended at the end of a fork, as with smaller doublets. This plan of mounting was unfortunate in the case of so large and heavy an instrument, especially at the latitude of Arequipa, since manipulation was made difficult and flexures were introduced. For use at the new South African station, the instrument is being remounted in the two pier arrangement. Thus equipped and placed it may confidently be expected to yield material of the highest value in the solution of the stellar problems under investigation by the present director of the Observatory.

Another doublet of special importance is the 16-inch Metcalf telescope. The lens was constructed gratuitously for the

Observatory by the late well-known amateur astronomer, the Reverend J. H. Metcalf. The definition is especially good. Valuable investigations have been greatly assisted by its use, such as the charts of the Kapteyn Selected Areas and of the Harvard Standard Regions for the northern sky, and the photographs for the determination of the position of the moon. Curved plates have been used with this telescope, the curvature being produced in the telescope with the aid of atmospheric pressure and an air pump. The field of good definition is thus considerably extended.

The Draper and Boyden Refractors.—These telescopes, one in the northern and the other in the southern hemisphere, are a pair of instruments by means of which any investigation within their scope can be made to cover the whole sky.

The 11-inch telescope was obtained by loan from Mrs. Draper, in 1886, in order to extend the work of the Henry Draper Memorial. Later it became the property of the Observatory by gift. Originally it was a visual telescope, made for Dr. Draper by Alvan Clark and Sons. It was adapted to photographic work by the use of a suitable correcting lens. To obtain the spectra of the brighter northern stars, from one to four objective prisms were placed over the lens. Spectra of the brightest stars were thus obtained having a length of about 5 inches, which showed in some cases many hundreds of spectral lines.

This instrument was used for many years at the Jamaica station by W. H. Pickering for visual observations of different members of the solar system. It has also been employed by King for obtaining out-of-focus images of the brighter stars for photometric determinations.

The 13-inch Boyden refractor, of unusual construction, has proved to be an exceedingly useful instrument. The crown lens is reversible, and its two faces have different curvatures. In one position, with the two lenses nearly in contact, the spherical and chromatic aberrations are corrected for the visual

rays. When the crown glass is reversed and separated somewhat from the flint glass, the aberrations are corrected for the photographic rays. The plan was devised by Edward C. Pickering, in consultation with the Clarks. The same idea was independently proposed by Sir George S. Stokes and Sir Howard Grubb at about the same time. In spite of some apprehension in regard to the outcome of this scheme, the results in the case of the 13-inch were satisfactory both visually and photographically. Visually, it has been used by W. H. Pickering and Douglass for observations of planetary detail, and by various observers for the measurement of double stars. Photographically, it led to the discovery of cluster variables by Bailey, and provided photographs of the spectra of the bright southern stars, a study of which was made by Miss Cannon.

The Polar Equatorial.—An interesting instrument in active use at the present time is the 12-inch polar equatorial, the mounting of which was devised by Gerrish. For many years Pickering, in his extension of the Harvard Photometry to faint stars, used the lens as a part of the 12-inch horizontal photometer. When the observations planned for that instrument were completed, the lens was taken for the construction of the polar telescope. The telescope itself is fixed in position, and the images of the stars are brought into the field by a movable mirror easily controlled by the observer. The axis of the instrument is parallel to the axis of the earth; the observer looks into the eyepiece in the direction of the south pole. The telescope is placed on the south side of the west wing of the main building, with the observing end brought into the window of a room on the second floor. The observer thus works in a comfortable room, always seated in the same place and looking in the same direction. The whole northern sky is at his command, with the exception of a small region near the north pole. This telescope has been found very convenient for various kinds of visual observations, especially of variable stars.

The Meridian Photometers.—Pickering, when he began his visual photometry of the stars, found no suitable photometer in existence and proceeded to devise such an instrument, in consultation with Alvan Clark and Sons. For the measurement of the brightness of the naked-eye stars, included in the early Harvard Photometry, an instrument having lenses of about 2 inches diameter was used. Later, for the extension of this research, a larger instrument was constructed on the same general principles. It will probably be sufficient to give a brief description of the second and larger instrument, which had lenses about 4 inches in diameter and was capable of measuring the light of stars as faint as the ninth magnitude. Like most of the visual photometers that have been used at the Harvard Observatory, it was a polarizing instrument, although the 12-inch meridian photometer devised and employed by Pickering for the measurement of faint stars made use of wedges and shades.

The 4-inch meridian photometer was provided with two object glasses placed side by side with a silvered glass mirror in front of each. The lenses were inclined slightly to each other, so that the light from both was brought into a single eyepiece. A double-image prism, placed near the eyepiece and at a distance from the objectives nearly equal to their focal length, divided the light received from each lens into two pencils. The pencil of ordinary rays from one lens was made to coincide with the extraordinary rays from the other lens, and the other pencils were excluded from the field of view. With one mirror the star used as the standard of comparison, generally α or λ Ursae Minoris for the northern sky, was brought into the center of the field. The mirror was capable of the small motion necessary to keep this star in the proper position. With the other mirror, which could be rotated readily so as to command the meridian sky from one horizon to the other, any star when near the meridian could be brought into the field near the image of the standard star. Their light was then equalized by the revolution of a Nicol placed in the eyepiece.

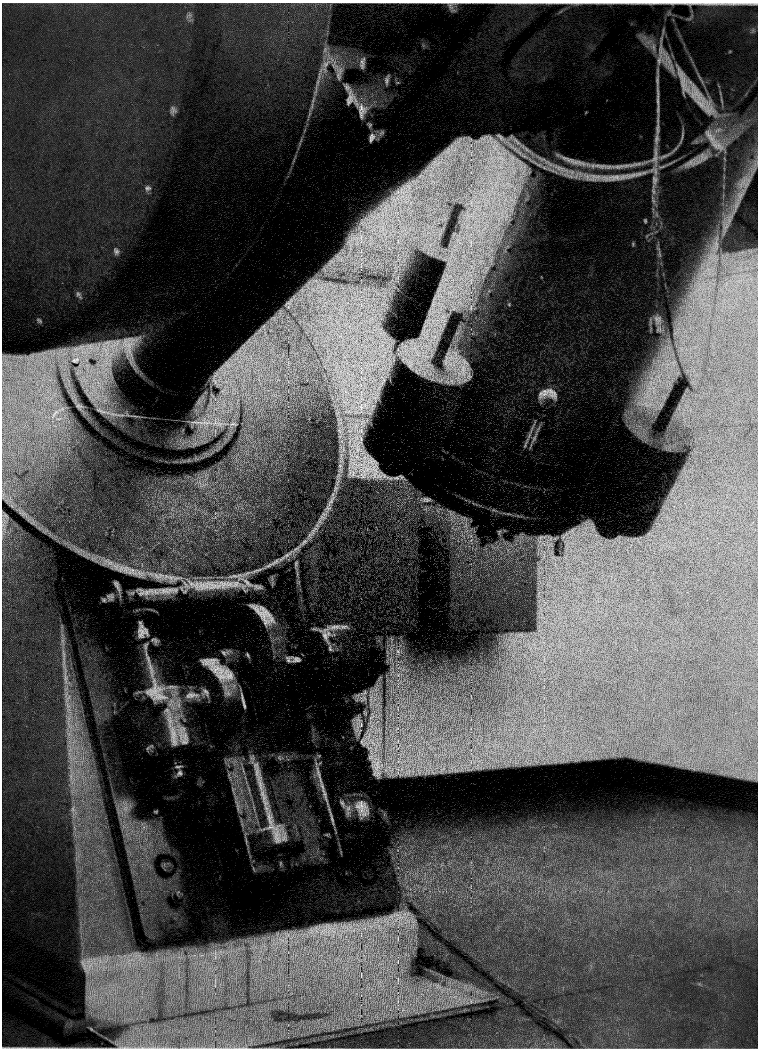

Plate V.—The 24-inch Bruce Telescope, as Newly Mounted at Mazelspoort.

(*Facing page 46*)

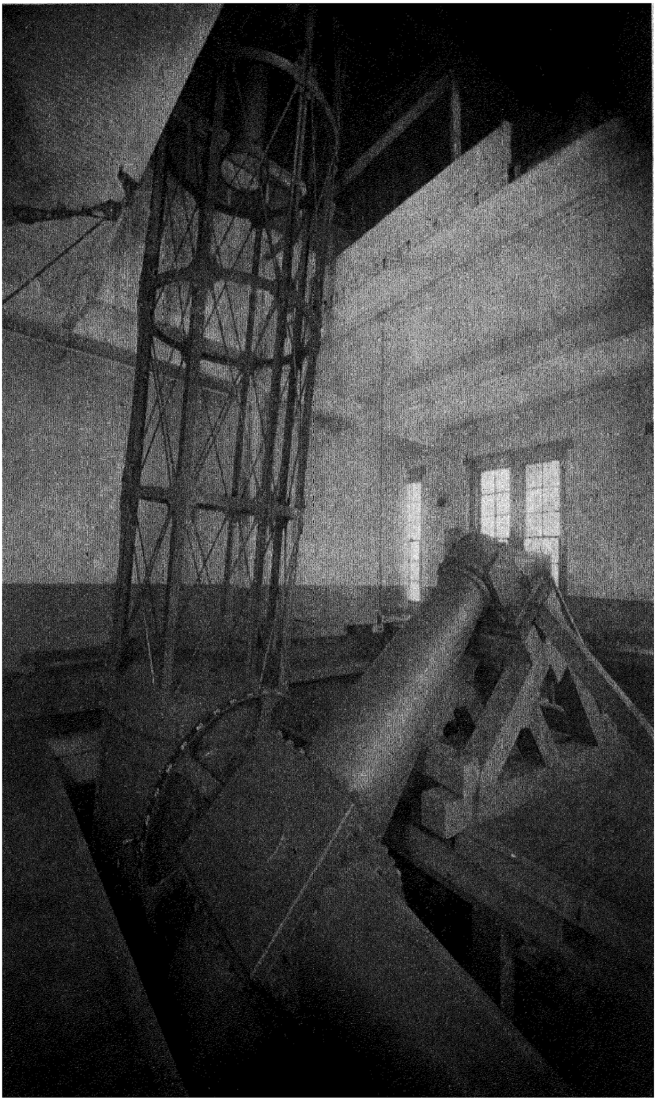

PLATE VI.—THE 60-INCH REFLECTOR, MOUNTED IN FECKER'S FACTORY AT PITTSBURGH.

As the Nicol revolved, the light of one star increased while that of the other decreased. Four different settings of equality were usually made, although in special cases the number was larger, the mean of all being regarded as one determination of magnitude. The observations were repeated on one or more nights. Suitable scales enabled the recorder to adjust the mirror for stars of any right ascension and declination, and to make a record of the readings of equality. The instrument itself remained in a fixed position, the observer facing east or west. For bright stars readily recognizable the settings of the instrument by the circles gave the desired star with small probability of error. For faint stars, the identification was checked by any catalogue stars which might be near. For zone work, the observer passed from one star to the next by the differences in right ascension and declination.

Pickering also devised various polarizing photometers for the photometric work carried on during many years, chiefly by Wendell, with the 15-inch refractor. The principles involved in their construction were somewhat similar to those of the meridian photometers, but with great differences in the details.

The 60-inch Reflector.—The Observatory obtained by purchase in 1904 the 60-inch reflecting telescope formerly used by Common, of England. With this instrument Pickering planned to extend the Harvard visual photometry to as faint stars as possible. Much time and labor were spent in fitting it for such observations. Owing to difficulties inherent in the telescope and its mounting, however, the definition of the stars was far from satisfactory. At about this time, also, the rapid development of the photographic photometry of the stars made a further extension of such work by visual methods less desirable. Little use was made, therefore, of this telescope, although some investigations were undertaken for the determination of the total intensity of stellar radiations, a field for which its great light-gathering power seemed to render it well fitted.

Dr. Shapley, in the plans for the extension of his researches into the extent of the visible universe, needed an instrument of greater power than any of those in use at the Observatory. One of the Common mirrors provided the glass for the mirror. It was found to be well suited to the purpose and was refigured. A mounting is being constructed (1927) by J. W. Fecker, successor to Brashear and McDowell. The new reflector will be sent to the station in South Africa; it will be the largest telescope in actual service in the southern hemisphere. The mounting is to be of the two pier type arranged for use in both the Newtonian and modified Cassegrainian combinations.

The great need of such an instrument is clearly set forth in the eighty second Annual Report of the Director:

> The Harvard Observatory has carried on fundamental surveying work in the southern skies for thirty seven years, attacking the numerous problems in a comprehensive manner, but seldom analytically. For example, the visual brightness, spectral classification, and variations in light have been studied for thousands of stars: a score of new stars have been found on plates made at the Boyden Station; some ten thousand nebulae have been discovered; and surveys of double stars, star clouds, gaseous nebulae, and star clusters have been products of the systematic work with the several photographic refractors. But searching analyses of special objects such as the Magellanic Clouds, globular clusters, gaseous nebulae, and individual stars have generally been impossible. The rapid photographic refractors and patrol cameras are suitable for the fundamental work and their use will be continued unabated, but a large well-equipped reflecting telescope is necessary for the special analytical studies.

Miscellaneous Instruments.—Several other instruments deserve special mention. The 10-inch triplet, in which a double concave lens has a central position and is used in making the final adjustments, was ground and figured by Metcalf. The definition given by this combination is unusually good over a large field. The triplet is similar in construction to that devised by H. Dennis Taylor, when a member of the English firm of T. Cooke and Sons.

A fixed photographic telescope, having a lens of 12 inches diameter, and of 135 feet focal length, with which W. H.

Pickering made systematic maps of the moon, was an interesting experiment, though not of great general utility.

The 24-inch reflector mounted at Cambridge has been of considerable value in obtaining material for special investigations.

Mention should be made of the development, by Gerrish, of electrical methods for the control of large instruments. The use of the electric motor synchronized by the pendulum of a standard clock, instead of heavy weights, for driving the instrument, as well as for securing slow motion in right ascension, has greatly facilitated the operation of heavy telescopes. This method was introduced for the 24-inch reflector in 1907, and was applied later to the 16- and 60-inch telescopes.

OBSERVATORY INSTRUMENTS*

60-inch Reflector (Two Mirrors)
†28-inch Draper Reflector
24-inch Bruce Doublet
24-inch Reflector
16-inch Metcalf Doublet
15-inch Equatorial Refractor
13-inch Boyden Refractor
12-inch Polar Equatorial
†12-inch (135-foot) Refractor
12-inch Metcalf Doublet
11-inch Draper Refractor
10-inch Metcalf Triplet
† 8¼-inch Meridian Circle
8-inch Bache Doublet
†8-inch Boyden Doublet
8-inch Draper Doublet
8-inch Refractor
†8-inch Polar Equatorial
†8-inch Doublets (Two)
†6¼-inch Equatorial Refractor
†5-inch Transit Photometer (Two)
†4¼-inch Transit Circle
†4-inch Meridian Photometer
†4-inch Comet-Seeker
4-inch Cooke Triplet
3-inch Ross Patrol Telescopes (Three)
2¾-inch Russian Transit
†2-inch Meridian Photometer

* As of 1929; small portable telescopes and photographic cameras are not included in the above list.

† Not now in active use.

CHAPTER V

EXPEDITIONS AND FOREIGN STATIONS

REFERENCE has been made in Chapter I to astronomical expeditions undertaken by members of Harvard University during the first two centuries of its existence. The Harvard Observatory since its foundation has carried out many scientific expeditions—several to observe total eclipses of the sun.

Total Eclipse of the Sun, 1851.—After the establishment of the Observatory, the first recorded attempt by a member of the staff to observe a total eclipse of the sun was made by George P. Bond in 1851. Taking advantage of a trip to Europe, he made observations of the eclipse of July 28, at Lilla Eden, Sweden. He was provided with a small telescope of about two inches aperture and a power of 30 diameters, which was loaned to him by Rümker of the Hamburg Observatory. The duration of totality was about four minutes. The conditions for observation were perfect, and the scenic setting added to the grandeur of the spectacle. Bond wrote a graphic account of the event which exists only in typewritten form. His scientific observations were published in the Astronomical Journal for October, 1851.[1]

Bond was much impressed by the pure white beauty of the corona and its visibility for an instant after the reappearance of the sun. His comments on the prominences illustrate the imperfect knowledge of that time regarding eclipse phenomena:

> . . . they had rather the appearance of flames, not in sudden motion, than of mountains, or of solid projections from the Sun, to which they seemed to belong rather than to the Moon, if they are not optical phenomena.

[1] A. J., 2, 49, 1851.

In the brief time at his command he recognized the real form of one of the bridge-shaped prominences, which have been so well shown in later years by photography.

Annular Eclipse of the Sun, 1854.—Careful preparations were made by the Observatory for the observation of the annular eclipse of the sun on May 26, 1854. An arrangement had been made with Dr. Bache, Superintendent of the United States Coast Survey, by which George P. Bond, Charles W. Tuttle, and Richard F. Bond, representing the Observatory, were provided with telescopes and time-keepers. They planned to observe the eclipse in New Hampshire from the summit of Mount Washington, near the northern limit of the annular phase. Unfortunately, after the laborious ascent of the mountain, a cold rain prevented any observations.[2]

Determinations of Longitude, 1855.—Some reference should be given to the various trips made in early days of the Observatory for the determination of longitude. Before the use of electrical methods, the determination of differences in longitude was frequently made by observations of celestial phenomena, and also by the transference of chronometers from one station to the other, generally in care of ship's officers. However, in order to obtain the best possible results for the difference in position of Liverpool and Cambridge, Mr. Sydney Coolidge, a volunteer assistant in the Observatory, took charge of the transportation of the chronometers in 1855. He also made the necessary transit observations both at Liverpool and at Cambridge. Under his direction some 50 chronometers were transported a distance of about 18,000 miles—a large undertaking in view of the slow ships of that day.[3]

Total Eclipse of the Sun, 1869.—The eclipse of 1869 occurred on August 7. Its path was from Alaska and Canada, through Iowa, Illinois, Kentucky, and North Carolina. It

[2] H. A., I, clxxviii, 1856.

[3] *Ibid.*, clxxxix.

aroused wide interest and was observed by nearly all American astronomers and by many from other countries. Congress made a liberal appropriation for its observation. At the request of Benjamin Peirce, Superintendent of the United States Coast Survey, Winlock, then Director of the Harvard Observatory, took charge of a party of observers at Shelbyville, Kentucky. He made photographs of the corona and carried on spectroscopic observations.

Other observers from the Observatory were Arthur Searle and C. S. Peirce, who were assigned to adjacent locations in the belt of totality. Peirce was stationed at Bardstown and Searle at Falmouth. Edward C. Pickering, at that time Professor of Physics at the Massachusetts Institute of Technology, made spectroscopic and other observations at Mount Pleasant. He also obtained a photograph of the corona with a portrait lens. Survey parties occupied stations in Alaska, Iowa, and Illinois, while representatives of other observatories and independent observers were distributed along nearly the whole path in the United States. The conditions of the sky were generally favorable, and the scientific results obtained added much to the knowledge of the nature of the sun.

Special attention was given to the form and nature of the corona, about which little was then known, and to the spectrum of the prominences. Photography was introduced on a scale hitherto untried. A photograph made at Shelbyville with an exposure of 40 seconds added to our knowledge of the form and extent of the corona. Winlock observed in the spectrum of the prominences during totality 11 bright lines of which 3 were visible before and after the total phase. He decided that all such photographs should be made at the principal focus, rather than with an enlarging lens, the more usual method at that time.[4]

Total Eclipse, 1870.—The success of the observation of the 1869 eclipse induced many American astronomers to observe

[4] H. A., **8**, 56, 1876; Rep., U. S. Coast Survey, 116, 1869.

that of the following year, on December 22, in Europe. Again the Government of the United States, through the Office of the Coast Survey, rendered important assistance. Benjamin Peirce still retained his position as Superintendent of the Survey, and was in general charge of American expeditions. Winlock, aided by Henry Gannett, an assistant at the Harvard Observatory, was placed in charge of the station at Jerez de la Frontera, Spain. Charles S. Peirce occupied a station in Sicily. Associated with Winlock in or near Jerez were a large number of observers, some of whom later became famous. Among them were Charles A. Young, Samuel P. Langley, and Edward C. Pickering. The sky on the day of the eclipse was rather cloudy, although at the time of totality the eclipse was only partially obscured. A number of photographs were obtained and many useful visual observations were made by members of the expedition.

For use at this eclipse, Winlock devised a special attachment for his spectroscope to ensure accuracy and speed in the determination of the positions of the lines observed. The arrangement consisted of a point or cutting tool attached to that part of the spectroscope which was moved to effect a pointing on a given line. The record of position was impressed upon a plate suitably placed. This apparatus appeared to work successfully, but its importance became less with the introduction of photographic methods. Winlock had also constructed a simple lens of long focus which was mounted in a fixed position, the image of the sun being kept in position by a movable mirror. This apparatus continued in use for a time at Cambridge for taking daily photographs of the sun. The method was not original with Winlock, but he seems to have been the first to bring it into practical use.

Photographs made at the eclipses of 1869 and 1870 are reproduced in the Harvard Annals. They were prepared in general by drawings, photo-engraving processes at that time not being well developed.[5]

[5] H. A., 8, 56, 1876; Rep., U. S. Coast Survey, 134, 1870.

Total Eclipse of the Sun, 1886.—W. H. Pickering, while he was a member of the faculty of the Massachusetts Institute of Technology, formulated plans for the observation of the eclipse which occurred on August 29, 1886. An account of this expedition is given here, because Pickering soon after became an assistant in the Observatory, and the Observatory provided a part of the equipment and published the results in the Annals. An appropriation of $500 was made by the Rumford Committee of the American Academy of Arts and Sciences to aid the expedition. This sum was to be applied to the purchase and transportation of the necessary equipment, and, if anything remained, to the cost of publication. Mr. Pickering paid his own personal expenses and depended entirely on volunteer assistants. The island of Grenada, in the West Indies, was chosen as the site for the observations. Clouds covered the sun on August 29 until within a few minutes of totality, when conditions became favorable. Visual observations of Baily's beads, shadow bands, and other eclipse phenomena were made by members of the party and by local volunteer observers. The principal instrument was a photo-heliograph of 38 feet focus, intended for a study of the structure of the inner corona and for a determination of its photographic intensity. Unfortunately, no satisfactory photographs were obtained with this instrument, although with others a few good plates were obtained, showing the prominences and the form and intensity of the corona. From these plates Pickering reached conclusions regarding the structure of the corona, and the visual and photographic intensity of the corona and of the sky.[6]

Total Eclipse of the Sun, 1887.—The Observatory took part by proxy in expeditions to observe the eclipse of August 19, 1887. It was uncertain at that time whether the corona was a fixed feature of the sun or whether it underwent rapid changes. To determine this, two widely separated stations, provided with similar apparatus, were needed. W. H. Picker-

[6] H. A., 18, No. 5, 1890.

ing prepared the instruments and plates for the experiment. Professor Charles A. Young at Rshev, Russia, and Professor David Todd, at Shirakawa, Japan, undertook to have the proper exposures made at these stations. Unfortunately, clouds prevented successful photography. Had the weather permitted, photographs would have been obtained at each station with a lens of 10 inches diameter and of such a focal length as to give an image of the sun 1 inch in diameter. In addition, in Japan, photographs had been planned to give images of the sun 5 inches in diameter without enlargement.[7]

The Boyden Expeditions, 1887 to 1888.—A fund amounting to about $238,000 was left by Uriah A. Boyden, of Boston. for carrying on astronomical observations at such an altitude as to avoid, so far as possible, the ill effects of the earth's atmosphere. Early in 1887 the trustees of this fund transferred it to the President and Fellows of Harvard College, for the use of the Observatory.

A search for the site where Mr. Boyden's wishes might best be carried out was at once undertaken, both by study and correspondence and by personal investigation. Altogether, a large number of more or less associated expeditions were undertaken, during many years, in the fulfillment of this obligation. The southern stations of the Observatory, first in Peru and Chile and later in South Africa, were selected and maintained in the spirit of Mr. Boyden's bequest.

Various appliances were devised to test the atmospheric conditions at different sites. These appliances included photographic instruments showing the definition of star images and trails and of trails of stellar spectra, at different localities and at various altitudes. Meteorological observations, when not already available, were undertaken by means of self-recording instruments.

E. C. Pickering and W. H. Pickering visited different localities and mountain summits in Colorado, in 1887. Records were

[7] Ann. Rep., H. C. O., p. 6, 1887.

continued after their departure by the aid of Professor F. H. Loud, of Colorado College. Much valuable information was furnished by General Greely, Chief of the United States Signal Service.

Through the assistance of Mr. W. H. Cilley, of the Oroya Railway, and Mr. V. H. MacCord, of the Southern Railways of Peru, meteorological observations were carried on during 1888 and 1889 to determine the desirability of a site in some elevated locality in Peru.[8]

Total Eclipse of the Sun, 1889.—The total solar eclipse of January 1, 1889 was observed by several members of the Observatory with a large equipment at Willows, California. W. H. Pickering had charge of the expedition, assisted by King, Black, and Bailey of the Observatory staff. Mrs. Bailey was one of a large number of volunteer assistants. Russell T. Crawford, later Professor of Practical Astronomy at the University of California, was at that time a boy of thirteen and a resident of Willows. He became an enthusiastic helper in the work of the station.

The instrumental equipment for the observation of the eclipse consisted of the 13-inch Boyden refractor, the 8-inch Bache doublet, and several smaller instruments. The condition of the sky on the day of the event was nearly perfect. Forty-seven photographs of different kinds were obtained, and numerous visual observations were made. Valuable meteorological observations were made by Professors Winslow Upton and A. Lawrence Rotch.[9]

A great crowd of onlookers gathered about the eclipse station. As the corona flashed suddenly into view at the instant of totality, a strange shout of applause, breaking a deep and impressive silence, rose from the multitude.

The Mount Wilson Station, 1889 to 1890.—After the eclipse of the sun at Willows, W. H. Pickering proceeded to southern California, which appeared to offer especial attrac-

[8] *Ibid.*, p. 8, 1887; p. 7, 1888.

[9] H. A., 29, No. 1, 1893.

tions for an observatory station. King and Bailey remained to pack up the equipment, a part of which was destined for some site in southern California and the remainder for Peru. Mr. Pickering consulted with several persons in Los Angeles and vicinity, and on January 23, 1889, accompanied by Alvan G. Clark and a number of volunteers from Los Angeles, passed a night on Mount Wilson. As a result of the information obtained, it was decided to establish a provisional station on the summit. After making some arrangements for this purpose, Pickering returned to Cambridge.

King, assisted by Black, was chosen to take charge of the installation and maintenance of the Mount Wilson Station. The instrument selected was the Boyden 13-inch refractor which had been successfully employed by King at the Willows eclipse, and which was now forwarded to Mount Wilson, where a suitable building was constructed for its protection. A shelter was also provided for the two observers. No good road to the summit existed at that time, and considerable difficulty was experienced in conveying the heavier parts of the instrument to the station. King and Black carried on observations in this isolated location from May to November, 1889, when King returned to Cambridge. The photographic work was continued into 1890 by Black, who then returned the instrument to Cambridge for transshipment to the Peruvian Station at Arequipa. The work carried out on Mount Wilson was chiefly photographic. Many successful plates were obtained of the moon, of planets, star clusters, double stars, and nebulae.

Although the advantages of the climate of Mount Wilson proved to be less satisfactory than had been anticipated, they were, nevertheless, considered sufficient to justify the purchase of a site and the foundation of a permanent station. For various reasons, however, the attempt to obtain a secure title was unsuccessful at the time, and later the establishment of the station in the southern hemisphere made one on Mount Wilson of less importance; hence the idea was abandoned.

Many years afterward, Edward C. Pickering, while on a visit to the mountain, made arrangements by which a memorial tablet was placed on the site of the Harvard pioneer station. It is near the present buildings of the Mount Wilson Observatory of the Carnegie Institution.

First Peruvian Expedition, 1889.—A recognition of the need for astronomical observatories or stations in the southern hemisphere was neither new nor peculiar to the Harvard Observatory. Astronomers everywhere appreciated the necessity of securing increased observations of southern stars. As soon as Pickering began the Harvard Photometry at Cambridge he was impressed with the desirability of extending the observations to the southern sky, and researches in stellar photography only emphasized the necessity for a Harvard southern station. The reception of the Boyden Fund made the establishment of such a station feasible.

At first, two stations were under consideration, one in the northern hemisphere so chosen as to fulfil the terms of the Boyden bequest, the other in the southern hemisphere. There appeared to be no good reason, however, why both considerations, a lofty site providing the best attainable atmospheric conditions, and a location somewhere south of the equator, might not be combined in a single station. For such a station the high plateaux and mountains of the west coast of South America seemed to offer many attractions, and correspondence was opened with various gentlemen in Peru. As a result of these investigations, a preliminary expedition was sent to Peru at the beginning of 1889, under the direction of S. I. Bailey, at the same time that another expedition, described above, was sent to test the climate of Mount Wilson, California.

On February 2, 1889, Mr. and Mrs. Bailey and their son Irving left San Francisco for Callao, Peru, on the *San José*, a ship of the Pacific Mail Company. At Panama they were joined by M. H. Bailey, who had with him additional apparatus brought directly from the Cambridge Observatory by way of

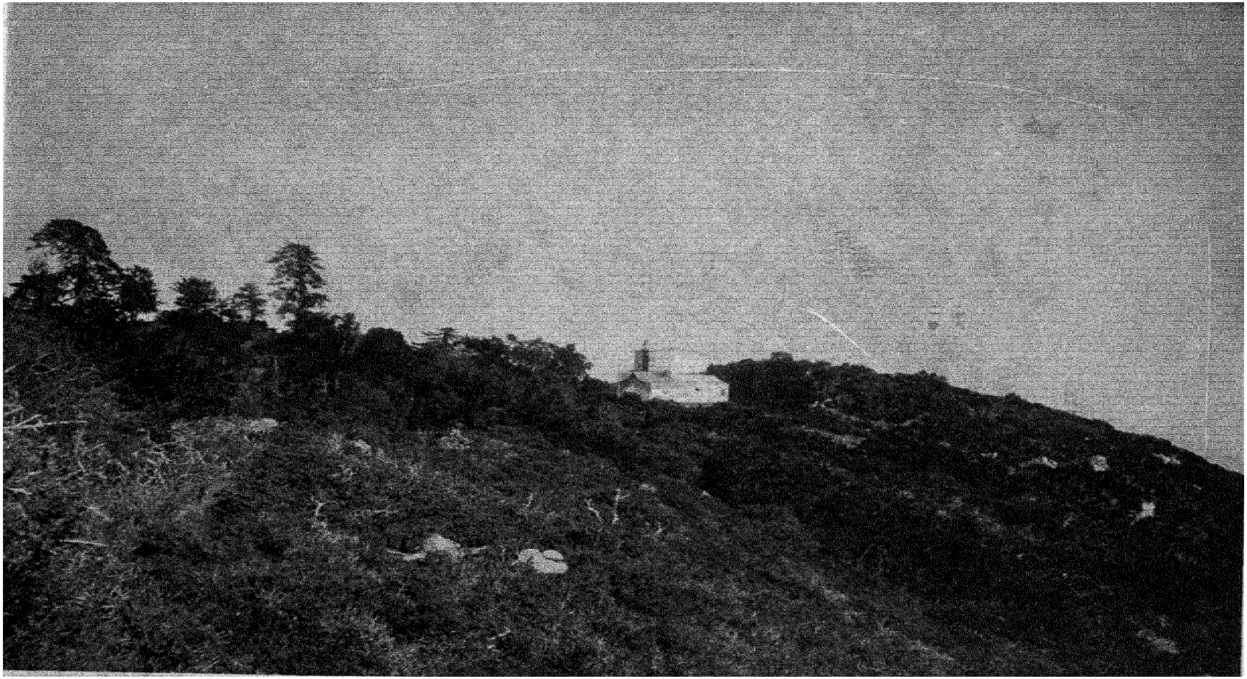

PLATE VII.—THE HARVARD STATION ON MOUNT WILSON, CALIFORNIA.

(Facing page 58)

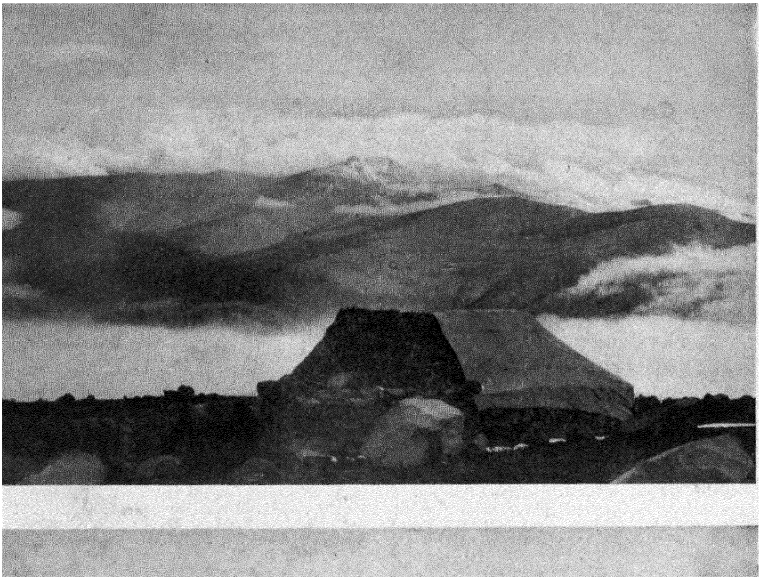

PLATE VIII.—(Above) MONT BLANC STATION, PERU. (Below) THE AREQUIPA STATION, WITH EL MISTI IN THE BACKGROUND.

New York. The chief instruments of the expedition were the 4-inch meridian photometer, which was to be used for the extension of the Harvard Photometry, and the 8-inch Bache doublet which had long been in use at Cambridge for making stellar charts and spectrum plates.

As a result of somewhat extended investigations along the Oroya railway, which runs from Callao through Lima to the lofty interior of Peru, a preliminary station was chosen near Chosica, a town lying in the valley of the river Rimac. The valley itself at Chosica, shut in by lofty elevations, did not give the desired horizon, especially to the north and south. A summit was therefore selected, 8 miles by mule trail from the village. This isolated site was occupied on May 8, 1889. Portable buildings of rather light construction had been sent from the United States. They served their purpose fairly well in the mild climate of central Peru, even at the altitude of 6500 feet. This hitherto unnamed summit was called "Mount Harvard." The members of the mountain camp were Mr. and Mrs. S. I. Bailey and son, Mr. M. H. Bailey, Señor Elias Vieyra, a Peruvian assistant, and two resident servants. A muleteer made a daily trip from the valley to the station, carrying food and water. Although 8 miles by trail from the nearest neighbors, the station was often visited by Peruvians and tourists, yet was never molested. It commanded a wonderful view of Lima and Callao, the Pacific Ocean 30 miles away to the west, the great Andes on the east, and endless mountain ridges and deep gorges on the north and south.

The sky at Mount Harvard became cloudy at the close of the southern winter, and a further study of the west coast was undertaken. Visits were made to Arequipa and vicinity, to the region about Lake Titicaca, and to the deserts of Chile, as far south as Valparaiso and Santiago. Two months were passed at Pampa Central, a nitrate center on the Desert of Atacama, in making observations for the Southern Harvard Photometry. The sky on the desert was found to be very clear, but living conditions would be both difficult and expen-

sive for an astronomical station unless it were associated with one of the large but uncertain nitrate or mining establishments.

As a result of all the investigations, Arequipa was recommended for a permanent station, and this choice was approved by the Director of the Observatory. On October 15, 1890, Mount Harvard was abandoned with regret, and the instrumental equipment was removed to Arequipa, where the sky remained favorable until about the middle of December. Late December, January, February, and March proved to be very cloudy, but the sky in April was exceptionally clear. During the cloudy season, under the efficient guidance of Señor Juan L. de Romaña, of Arequipa, the various desirable sites in the vicinity were carefully examined. The clear sky of April permitted the completion of the observations for the Southern Harvard Photometry, and, after assisting in the installation of the new Arequipa Station, the Baileys returned to Cambridge in May, 1891.[10]

Second Peruvian Expedition, 1891; the Arequipa Station.—On January 17, 1891, Professor W. H. Pickering arrived at Arequipa, accompanied by his family and by Messrs. A. E. Douglass and George Vickers, assistants. They carried with them the main equipment for the station, consisting of the 13-inch Boyden telescope and various smaller instruments. To these was added the apparatus used on Mount Harvard, with the exception of the meridian photometer, which was returned to Cambridge. Mr. Pickering selected a site for the station which had been highly recommended by Señor Romaña. It was situated two miles northwest of Arequipa at an elevation of over 8000 feet above sea level, and 500 feet above the city. A suitable residence, a laboratory, and buildings for the various instruments were constructed within a few months.

The Arequipa Station of the Observatory remained in charge of Mr. Pickering during the following two years. From 1893 until 1905, and in 1922 and 1923, it was in charge of S. I.

[10] H. A., 34, Chap. 1, 1895.

Bailey for most of the time. In other years it has been, for a longer or shorter period, in charge of H. C. Bailey, R. H. Frost, Leon Campbell, Frank E. Hinkley, L. C. Blanchard, J. E. Muñiz, and John S. Paraskevopoulos. The other members of the staff are listed in Chapter XX.

The station at Arequipa was maintained in active service until 1927, a period of 36 years. A sufficient account of the work done there is given in later chapters. In general the observations were planned by the director in Cambridge, and consisted in the extension to southern stars of the various researches begun at Cambridge. At first many visual observations were made, such as those of the Southern Harvard Photometry and its extensions, and the lunar and planetary observations of W. H. Pickering and Douglass. Later the work became more and more photographic. A few independent investigations were made, such as the planetary work of W. H. Pickering and the discovery of cluster variables by Bailey.

Minor Peruvian Expeditions.—Various secondary expeditions were undertaken by different members of the Arequipa staff during the life of the station. In 1891, W. H. Pickering, Douglass, and Vickers visited Bolivia and did some topographical work involving the measurement of several mountain elevations, both in Peru and in Bolivia.

Under W. H. Pickering's direction, several visits were made to the flank of the mountain range Chachani, 20 miles north of Arequipa. A meteorological shelter was placed at an altitude of 16,500 feet, and an unsuccessful attempt was made to reach the summit, about 20,000 feet in elevation. While returning to the United States, he obtained successful observations of the total eclipse of the sun at Mina Avis, near Vallenar, Chile, on April 16, 1893. He was accompanied by Professors A. Lawrence Rotch and A. E. Douglass.[11]

In 1893, as a result of several exploratory trips made by S. I. Bailey and other members of the staff, a meteorological

[11] Astr. and Ap., 12, 461, 1893.

station was installed on the summit of El Misti, a nearly extinct volcanic cone 19,200 feet high, about 11 miles northeast of Arequipa. There was at that time a desire among meteorologists to obtain observations at the greatest possible elevations. The Misti summit station was maintained for about eight years, although not continuously. Visits to the summit proved impracticable during the summer months when the mountain was deeply covered with snow. Self-recording instruments were employed which ran for 10 days without rewinding, and eye observations were made when an observer was present. The Misti Observatory appears to have been the loftiest scientific station ever maintained. In connection with the stations on the summit and flank of the mountain, a series of similar meteorological stations were maintained for many years, extending northward from the Pacific Ocean at Mollendo across the western cordillera to the high plateau, and thence beyond the eastern Andes to the valley of the Urubamba, at Santa Ana, Peru. All of these stations were occasionally inspected by a member of the Arequipa staff. The observations were made, in general, by resident natives, in some cases gratuitously.[12]

Professor Winslow Upton, of Brown University, and formerly an assistant in the Observatory, passed ten months at the Arequipa Station, during the years 1896 and 1897, for the purpose of determining its precise geographical position. His outfit consisted of two portable transit instruments, two mean time chronometers, a sidereal clock, a sextant, an engineer's transit, and several minor instruments. Assistance was given by members of the Arequipa Station. Telegraphic signals were exchanged between the station and Arica, Chile, whose position was accurately known. All of the observations at Arica were made by Professor Upton. The resulting longitude of the transit instrument of the Arequipa Station was $4^h\ 46^m\ 11^s.73$ west of Greenwich. The latitude was found to be $-16^\circ\ 22'\ 28''.0$, and the altitude above mean sea level, 8043 feet.

[12] H. A., 39, 1906; 49, 1, 1907.

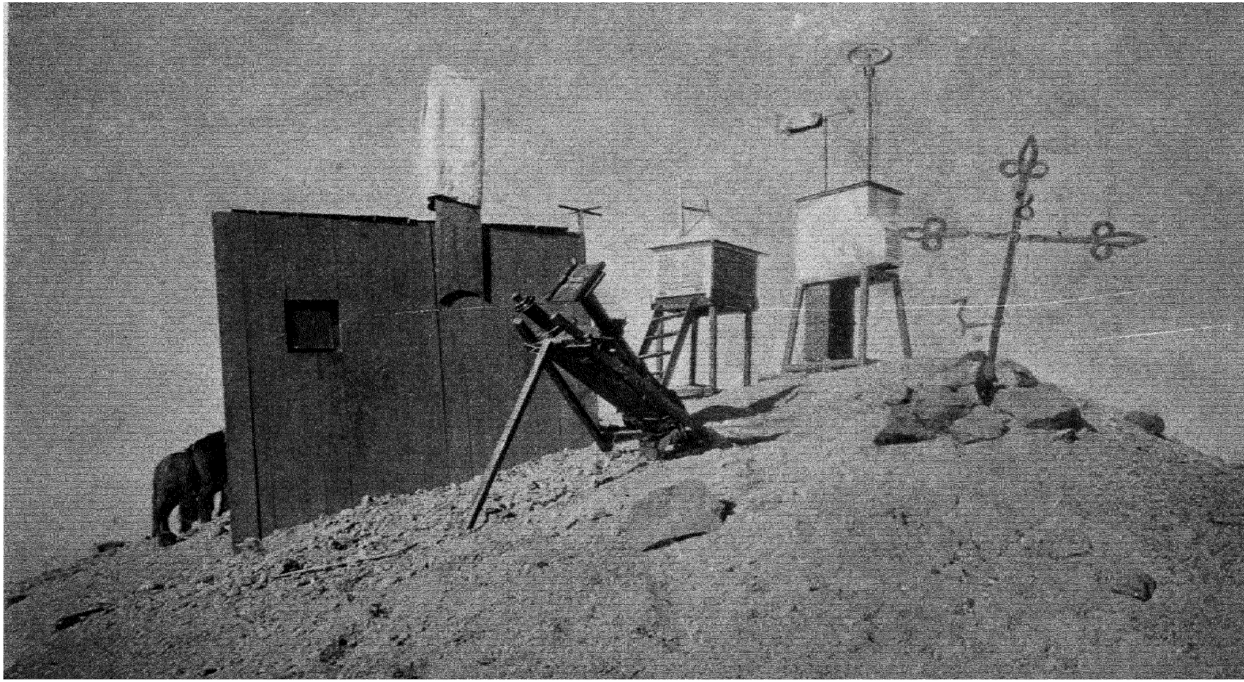

PLATE IX.—THE METEOROLOGICAL STATION AT THE SUMMIT OF EL MISTI.

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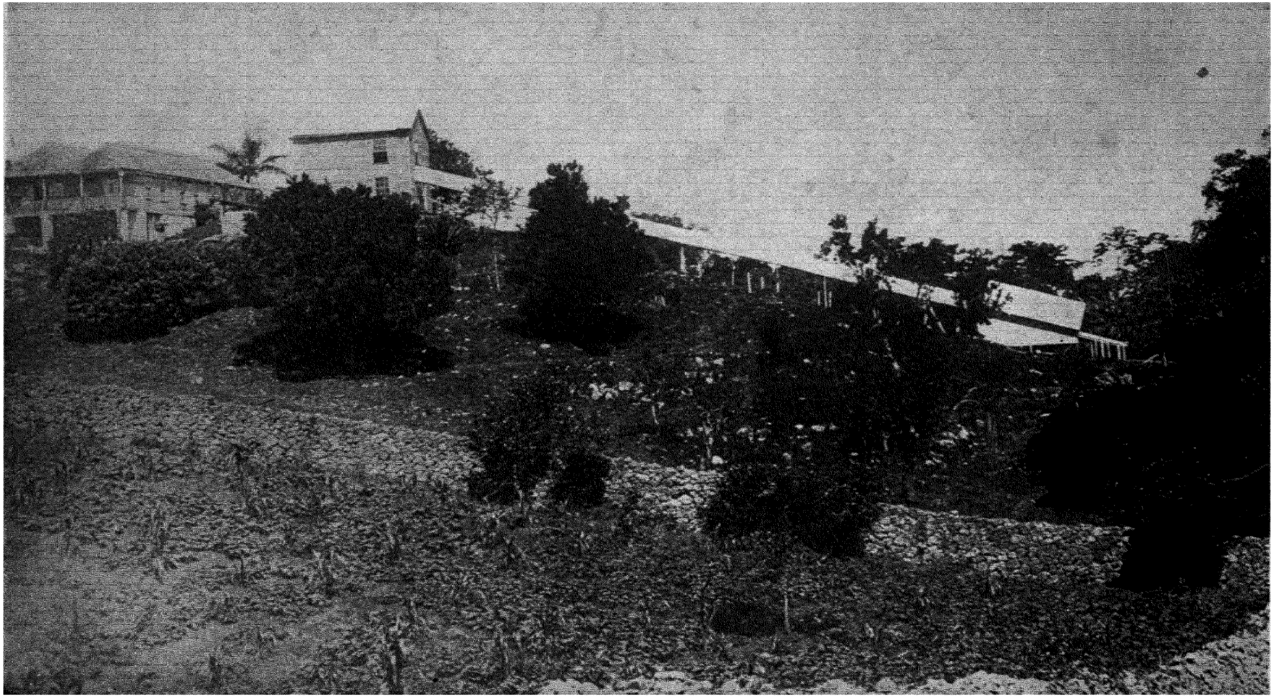

PLATE X.—THE 135-FOOT TELESCOPE, MANDEVILLE, JAMAICA

Mr. Upton also determined the relative positions of various points in the vicinity of Arequipa.[13]

First Jamaican Expedition, 1899.—An expedition was undertaken by W. H. Pickering to test the "seeing," and to determine whether the island of Jamaica offered favorable atmospheric conditions for the use of a large telescope. Tests were made with a five-inch telescope at various localities, a standard scale of seeing devised by W. H. Pickering and Douglass being used. The results of such tests made during July and August, 1899, were compared with the results of similar tests made at Cambridge both before and after the trip. The atmospheric conditions in Jamaica were found to be favorable in several localities, especially at Mandeville.[14]

Total Eclipse of the Sun, 1900.—An expedition undertaken largely at the expense of the Observatory, was sent to Washington, Georgia, on May 28, under the direction of W. H. Pickering. The special object of the expedition was a search for a possible intra-mercurial planet. Unfortunately no satisfactory results were obtained. Good photographs of the inner corona and prominences, however, were made at Wadesboro by an expedition sent out by the Secretary of the Smithsonian Institution, which used a new telescope of 135 feet focus, loaned by the Harvard Observatory.[15]

Second Jamaican Expedition, 1900 to 1901.—A second expedition to Jamaica was undertaken by W. H. Pickering, assisted by E. R. Cram, to test the value of a telescope having a lens of moderate aperture and great focal length. For this purpose a lens had been made with a diameter of 12 inches and a focal length of 135 feet. The instrument had already been found useful at the total eclipse of 1900, as stated above. It was sent to Jamaica later in the same year. At Mandeville, the lens and the photographic tailpiece were placed in different

[13] H. A., 48, No. 9, 1903.
[14] H. A., 51, Chap. 2, 1903.
[15] Ann. Rep., H. C. O., p. 16, 1900; Pop. Astr., 8, 225, 1900.

shelters connected by a covered way. The light was thrown on the stationary lens by a movable mirror having a diameter of 18 inches. The observations, of which an account is given in Chapter VII, were chiefly of the moon, and were made from January to August, 1901. Some investigation was also made of the suitability of the instrument for stellar photography. In his Annual Report for 1901, the director, E. C. Pickering, states: "The long-focus telescope is, therefore, again in Cambridge. Apparently an instrument of this form is not well adapted to the study of the stars, unless it can have a much larger aperture."[16]

First South African Expedition, 1908 to 1909.—After nearly 20 years' trial of the climate of Arequipa, it seemed important to investigate whether better conditions were to be found elsewhere for the southern station of the Observatory. Arequipa is in many respects an almost ideal site. For six months of the year, from May to October, the conditions leave little to be desired. Not only is the sky sufficiently clear, but the steadiness of the air, the moderate diurnal range of temperature, and the absence of dew are most satisfactory. Occasionally such conditions prevail throughout the greater part of the year, leaving a short and broken cloudy season. Ordinarily, however, the cloudy season is long and unbroken, interfering seriously with the work of the station.

The elevated plateau of South Africa had been highly commended to Pickering by Sir David Gill, Sir William Morris, and others familiar with its characteristics. Accordingly an expedition in charge of Bailey was sent to investigate the country. A visual telescope of 10 inches aperture, one of 5 inches aperture for testing the seeing, a photographic camera, and a varied equipment for meteorological observations, were provided.

Brief preliminary visits were made to various localities in Cape Colony, the Orange River Colony; the Transvaal,

[16] H. A., 51, 1903.

and Rhodesia. Hanover, on the Upper Karoo, most highly recommended by Sir William Morris and others, was selected as the principal station for more detailed investigation. The 10-inch telescope was set up and provided with a suitable shelter, and astronomical observations were carried on whenever possible. Systematic meteorological observations were also made at Bloemfontein, largely through the volunteer assistance of Mr. James Lyle, and at Worcester by the aid of Mr. Izak Meiring. Mr. L. S. Schultz, a resident of Hanover, was engaged as an assistant to aid in the observations in that village. The meteorological observations at those three stations were continued throughout the year 1909. Bailey returned to Cambridge in December of that year, but the Hanover station was left in care of Schultz, who carried on observations for several months in 1910. Toward the end the observations were irregular and unsatisfactory, and the station was closed.

The results of the expedition can be summarized briefly. The high plateau of South Africa offers many inducements for the establishment of a permanent astronomical station. The conditions are good over a wide area. The amount of clear sky and especially its distribution throughout the year, are much more favorable than at Arequipa. On the other hand, the steadiness of the atmosphere, though good, is no better than that of Arequipa, and the diurnal range of temperature and the precipitation of dew are greater. Dust storms and violent thunderstorms are also common in South Africa. From a purely scientific standpoint, Hanover, an attractive but isolated village, offers very strong advantages. The conditions at or near Bloemfontein are almost equally good, however, and the social advantages for a scientific staff, incomparably superior. The conditions at Worcester are good, with an almost uniform distribution of the cloudiness throughout the year, but the sky is distinctly less transparent than on the plateau. Johannesburg has the social and other advantages of a large city, and also favorable climatic con-

ditions. Regarded from all considerations, Bloemfontein appeared especially favorable, and is probably not surpassed by any other locality in South Africa for an astronomical observatory. No action was taken at the time, however, since the financial condition of the Observatory did not then permit the large expense involved in transferring the station from Arequipa to South Africa.[17]

The Station at Mandeville, Jamaica, 1912.—W. H. Pickering became permanently established at Mandeville in 1912. Little photographic work has since been done at the station. Mr. Pickering has devoted his time chiefly to visual observations of the moon and planets, using the 11-inch Draper refractor. The station was a part of the Harvard Observatory and was maintained by it until Pickering's retirement from the staff in 1924. Since that time he has maintained the station as a private observatory. The 11-inch telescope is now in Cambridge, where in recent years it has contributed significantly to the new developments in the field of spectrophotometry.

Chuquicamata and San José Stations, 1923 to 1926.— Dr. John S. Paraskevopoulos was placed in charge of the Arequipa Station late in 1923. By request of the director, Dr. Shapley, he undertook, in December, 1923, an expedition to Chuquicamata, a mining town in the desert region of north-eastern Chile. The region had long been known to have a favorable sky. At Arequipa, the conditions are satisfactory for six or eight months, but from December to March, the southern summer, the sky is usually almost continuously cloudy at night. As far back as 1890, it had been shown by Bailey, as a result of two months passed at Pampa Central, a nitrate town in the desert southwest of Chuquicamata, that the region gave good conditions during the months most cloudy at Arequipa. In more recent years, observations made by L. B. Aldrich at a station near Chuquicamata, maintained

[17] Ann. Rep., H. C. O., 1908, 1909, 1910; Sci. Mon., 21, 225, 1925.

by the Smithsonian Institution for the study of the sun, showed that excellent conditions prevailed there throughout the year.

Paraskevopoulos took with him to Chuquicamata in December, 1923, two photographic telescopes of moderate size, and carried on work during the months most cloudy at Arequipa. The results were very satisfactory. A second expedition to the same site in the cloudy season of 1925 to 1926 gave similar results.

During the intervening cloudy season of 1924 to 1925, a study was made by Paraskevopoulos of the conditions at San José, a railway station on the desert between Arequipa and the Pacific Ocean. A station in this vicinity, since it is near to Arequipa and accessible by rail, would have been much more convenient than one in Chile, had it proved favorable. The conditions proved to be very poor, however, and the observations appeared to demonstrate that no advantage would be gained by moving to San José, or to any site on the Desert of Islay.

The continuance of the station at Arequipa alone involved the loss each year of about four consecutive months. The selection of Chuquicamata alone as the site of the southern station would, indeed, provide a very clear sky, but an extremely inhospitable desert site. To occupy permanently two widely separated stations would involve many inconveniences. It would cause much extra labor, greater expense, a larger equipment, and considerable loss of time. Under these circumstances, Dr. Shapley decided to remove the Arequipa Station to South Africa.

Total Eclipse of the Sun, 1925.—Observations of the eclipse of January 24, 1925, were undertaken at several widely separated stations. The chief object was a determination of the total light of the corona by a plan devised by King. Shapley was at Buffalo, New York, where clouds interfered. Miss Cannon was stationed at Poughkeepsie, New York, Campbell

at New London, Connecticut, and King and Miss Payne on Nantucket Island, where Miss Harwood, Director of the Maria Mitchell Observatory, took part in the observations. Dr. W. J. Fisher observed the eclipse near North Falmouth, Massachusetts, at the northern edge of the path of totality. Dr. W. J. Luyten made observations near New York City, from an airplane, which was prepared, if necessary, to rise above any obscuring clouds. Nearly all the members of the Cambridge Observatory visited the path of totality. It is doubtful whether a total eclipse of the sun was ever seen before by so many individuals. The conditions were favorable in most localities, and the interesting event was observed by several million people. Many special trains were run to favorable localities from Boston and other large cities.

From the numerous photographs obtained of the corona, King found among other things that the integrated brightness of the corona within a circle 3° in diameter, in stellar magnitudes, is -10.96 photographic, and -11.61 photovisual, with a color index of $+0.65$, corresponding in spectrum to a star of Class G0.[18]

Additional results were obtained from photographs made at the Maria Mitchell Observatory by Miss Harwood. The integrated photographic magnitude of the earthlight on the full disc of the moon was found to be -3.20.[19]

The New Southern Station at Mazelspoort, near Bloemfontein, 1927.—Generous gifts from the International Education Board and from Harvard University provided funds in 1926 for the transfer of the Boyden Station to a more favorable locality. Dr. Shapley finally decided to remove the station from Arequipa, Peru, to a site near Bloemfontein, O.F.S., South Africa.

A beginning was made in dismounting the various instruments at Arequipa in November, 1926, and in February,

[18] H. C. 286, 1925; Pop. Astr., 33, 289, 1925.
[19] H. C. 312, 1927; Pop. Astr., 33, 344, 1925.

1927, they were forwarded to Bloemfontein. The Bruce telescope, however, was sent to Pittsburgh, Pennsylvania, where a new mounting was to be constructed by Mr. J. W. Fecker, before its transshipment to South Africa. Dr. and Mrs. Paraskevopoulos reached Bloemfontein in July, 1927. After some investigations into the desirability of various localities near that city, a permanent site was chosen at Mazelspoort, about 14 miles northeast of Bloemfontein. The position of the new Boyden Station is approximately $1^h\ 45^m\ 37^s$ east longitude and 29.2° south latitude. The altitude is about 4500 feet. Assistance in preliminary explorations for a site was rendered by Professor R. A. Rossiter, Superintendent of the Bloemfontein Station of Detroit Observatory of the University of Michigan. The City of Bloemfontein made generous financial contributions to the establishment of the Harvard Station, by the building of roads, by the laying of water, power, and telephone lines, by expert engineering service, and in other ways. The station is on the summit of a "kopje," or hill, near the water and electric plants of the City of Bloemfontein. By the end of 1927, considerable progress had been made in the building of the new station.

CHAPTER VI

PUBLICATION OF SCIENTIFIC RESULTS

The Harvard Annals.—The founders of the Observatory early recognized that the success of a scientific institution must be judged mainly by its published results. "Statutes" for the guidance of general policies, and "Regulations" in regard to the publication of observations, prepared by President Jared Sparks, were passed in December, 1849. Among the regulations it is ordered that:

> The publication shall be entitled, Annals of the Astronomical Observatory of Harvard College; the volumes, or parts of volumes, shall be uniform in size, quality of the paper, and style of execution, and the title-page of each volume shall bear an inscription indicating from what source the means of printing it were derived.[1]

The Annals thus became the official publication for the more extensive investigations of the Observatory. Begun under the Bonds, they have been carried forward by Winlock, Pickering, and Shapley, and their associates, until at the present time they consist of nearly 100 quarto volumes.

The nature of the Annals has changed considerably; the contents of early volumes are more general than those of recent times. Volume 1 contains the early Annual Reports of the Director and of the Visiting Committee, important correspondence regarding policies and instruments, and other matters not purely astronomical. Also, during the early years, and especially during Pickering's administration, meteorology received much attention. This was in harmony, nevertheless, with the Statutes of the Observatory, which state:

> The objects of the Observatory are, to furnish accurate and systematic observations of the heavenly bodies for the advancement of Astronomical

[1] H. A., 1, lxii, 1856.

Science, to cooperate in Geodetic and Nautical Surveys, in Meteorological and Magnetical Investigations, to contribute to the improvement of Tables useful in Navigation, and, in general, to promote the progress of knowledge in Astronomy and the kindred Sciences.[2]

William C. Bond's interests and observations related chiefly to geodesy and navigation; and magnetic and meteorological observations occupied the attention of the volunteer assistants at the old Dana House Observatory. Under Pickering's administration an intimate relation existed between the Astronomical Observatory and the Blue Hill Meteorological Observatory, which later became a separate department of the University, though its observations for many years had been published in the Annals.[3] Certain observations of the New England Meteorological Society and the New England Weather Service also appeared in the Annals.[4] In connection with the study of climatic conditions at the southern stations of the Observatory, many meteorological observations were made which have been published in the Annals under the heading "Peruvian Meteorology."[5]

At the present time, the work of the Observatory is confined chiefly to astronomical investigations, and the Annals contain only the results, usually in catalogue or tabular form, of the larger researches, such as the great catalogues of the Harvard Photometry and its extensions, and especially the Henry Draper Catalogues of stellar spectra.[6]

The Harvard Circulars.—For the prompt announcement of the results of its work, the Observatory began in 1895 the publication of Circulars. As planned by Pickering, these Circulars were to be somewhat comprehensive in their scope, in order to include the results of recent observations, new plans of work, gifts, and bequests, and, indeed, any subject

[2] *Ibid.*, lix.
[3] H. A., 20; 30; 40; 42; 43; 58; 68; 73; 83; 86, Parts 1, 2, 4; 87, Part 1.
[4] H. A., 21; 31; 41, Nos. 1–4.
[5] H. A., 39; 49; 86, Part 3.
[6] H. A., 14; 23; 24; 26; 27; 28; 34; 44; 45; 46; 50; 54; 91–100.

of astronomical interest. They generally contained a few quarto pages. At the present time, with the changed character of the Bulletins, the Circulars are confined more strictly to purely astronomical subjects, and contain such single investigations as in earlier years would have formed Numbers in volumes of the Annals devoted to miscellaneous researches. The number of Circulars issued up to the end of the year 1927 was 319.

The Harvard Bulletins.—The Harvard Observatory has always made some effort to announce important astronomical discoveries to the public as well as to other observatories. In his Annual Report for 1883, Pickering described an important extension of the system of announcing astronomical discoveries by telegraph and cable, a service that had been in use for a number of years. An association of 50 European observatories was formed with headquarters at Kiel, for the purpose of giving prompt information about astronomical discoveries in different countries. An American service of this nature, which had previously been rendered by the Smithsonian Institution, was transferred to the Harvard Observatory as the American counterpart of the European bureau.

For a long time this service was telegraphic only, but in 1898 the Harvard Bulletins were introduced in order to supplement the telegraphic service by promptly mailed announcements of important discoveries. For many years the Bulletins were devoted chiefly to cometary announcements. At first they were neostyled from hand-written copies, but beginning with No. 501, issued on October 1, 1912, the Bulletins have been printed. Later the scope of the Bulletins was extended to include notes on novae, variable stars, and other objects.

Under Dr. Shapley's direction the nature of the Bulletins has been completely changed. They have taken on in large measure the character of the Circulars, but each contains several communications instead of only one. Since October, 1926, they have generally been issued regularly on the first day

of each month, and have been much enlarged, containing announcements on many subjects under investigation in the Observatory. The number of Bulletins issued up to the close of the year 1927 was 853.

Harvard Announcement Cards.—The change in the scope and periodicity of the Bulletins left a need for prompt announcements, and the Harvard Announcement Cards were begun on March 12, 1926. This series of cards gives immediate distribution to astronomical announcements received by telegram. They are similar in purpose to the early Bulletins. They can be sent out much more promptly than the present Monthly Bulletins, and they relieve them from including telegraphic announcements regarding comets, novae, asteroids, and similar matters.

Harvard Reprints.—In 1923, in order to bring together into convenient and accessible form various astronomical communications made by members of the Observatory to different scientific journals, a series of reprints was inaugurated. By the end of 1927 the number of such reprints was 42. Prior to the beginning of this series, a large number of astronomical papers had been published by members of the staff in various journals, and can be found only by laborious searching of the indices. The Bonds, in addition to their contributions to the Annals, published nearly 200 papers in outside journals, and during the long directorship of Pickering the number of such contributions was also very large; they appeared in the publications of the American Academy of Arts and Sciences, in the Monthly Notices of the Royal Astronomical Society, the Astronomische Nachrichten, the Astronomical Journal, and elsewhere. Recently, such papers have appeared chiefly in the Proceedings of the National Academy of Sciences, Popular Astronomy, and the Proceedings of the American Academy of Arts and Sciences. Many of the earlier communications were important scientific treatises; others were more in the nature of announcements of astronomical discoveries. Even a proper

index of them all would fill a small volume, and although its inclusion here would be desirable, it is evidently impossible.

The Annual Reports.—The Report of the Director was first issued in 1846, and the Annual Reports have since been continued without interruption; all have been published except those for the years 1856 to 1858, and 1874 to 1876. They give a synopsis of the work and needs of the institution, and provide a brief history of its activities. The earliest numbers were published in the first volume of the Annals. Later numbers were included in the Annual Reports of the President of the University, and were also issued as separate reprints.

Additional notes on the activities of the Observatory can be found in the Annual Reports of the Visiting Committee, which were also begun in 1846 and were continued with few breaks for many years. The early reports were printed in the first volume of the Harvard Annals. When made in writing, they have also been published by the University in connection with the reports of the Visiting Committees appointed by the Board of Overseers for the various departments of the University.

Harvard Monographs.—A series of Monographs was begun in 1925 with the publication in book form of "Stellar Atmospheres," by Miss Payne. The Monographs were designed to have a larger scope and rather a more readable form than the more restricted Circulars and Bulletins. It is planned that other volumes of a monographic nature will be issued in the same form. The second of the series is Dr. Shapley's monograph on star clusters—a summary of his own contribution to the subjcet and of other relevant investigations, and containing a large amount of material not published before. The third is a spectroscopic study, by Miss Payne, of the high luminosity stars—supplanting many sections of her earlier book and carrying further the problems outlined there. The present volume is the fourth of the series. Volumes dealing with meteoric problems, by Dr. Fisher, and with long period

variables, by Dr. Shapley, Mr. Campbell, and Miss Payne, are in preparation or under consideration.

Miscellaneous.—In addition to its printed publications, the Observatory has issued astronomical photographs and lantern slides, not only for the use of astronomical societies, but for the instruction of students and the public. An exhibition of illuminated transparencies of celestial objects has long been a permanent feature of the Observatory, and similar glass positives have been sent to other places to form a part of such exhibitions. Most students and visitors can gain much more information from an inspection of such photographs than from observations with the telescope.

Funds for publication were lacking during the early years of the Observatory. Such funds have since been provided, but not in such amount as to avoid the necessity for great care and economy. At all times the Observatory has depended in part on special gifts to prevent serious delay in the publication of the results of its work.

PART II

THE SCIENTIFIC PROBLEMS

CHAPTER VII

THE SOLAR SYSTEM

The Brightness of the Sun.—Although systematic and extended solar research has never been a part of the Observatory program, interesting pioneer work has been done on sunspots, on the solar spectrum, and especially on the photometry of the sun. One of the earliest contributions from the Observatory was a series of sunspot drawings for the years 1847 to 1849, by William C. Bond. These, with brief notes, were published after much delay in 112 plates.[1] The series, of course, does not compare favorably with later photographic work, but since they antedate solar photography the plates are of considerable value. A large number of fine drawings of solar spots and prominences were also made by Trouvelot in the years 1872 to 1874, specimens of which were reproduced in the Annals.[2]

Many determinations of the brightness of the sun, expressed in stellar magnitudes, have been made by astronomers, the light of the sun being compared with that of Sirius and other stars. As early as 1860 George P. Bond determined the relative light of the sun and moon, and compared sunlight with the light of various celestial objects. He found that the sun gives us nearly 6,000,000,000 times as much light as Sirius, over 3,000,000,000 times as much light as Jupiter at opposition, and 622,600,000 times the light of Venus at maximum. Such difficult comparisons of sunlight and starlight are never made by the casual observer of the heavens—he is more likely to compare the brightness of the sun and moon; Bond found that

[1] H. A., 7, 1871.
[2] H. A., 8, Part 2, 1876.

the sun gives us 471,000 times as much light as the mean full moon.[2a]

One of the objects of the second Jamaican expedition, undertaken in 1900, was to obtain, if possible, satisfactory determinations of the brightness of the sun and moon. Extensive observations were made, and the sun's light was compared with that of Sirius, Capella, Arcturus, and Vega. As a mean of the results of these comparisons, William H. Pickering found -26.83 for the visual magnitude of the sun.[3] In other words, the sun gives about 10^{10} times as much light as a first-magnitude star.

Among the more important contributions from the Harvard Observatory to solar astronomy is the determination of the photographic and visual magnitudes of the sun by Edward S. King—an investigation extending from the year 1903 to 1910, and culminating in the values -25.83 and -26.81, respectively.[4] Although carried out by different and independent methods, these results by King agree closely with those obtained by the Pickerings.

To test the constancy of the sun's magnitude, Leon Campbell undertook in 1917 a long series of visual photometric observations of the planet Uranus, following a suggestion of Edward C. Pickering that any conspicuous variations in the total solar radiation should be revealed by accurate photometry of Uranus, whose light could be directly compared with that of neighboring stars. Campbell found, not a variation in the sun's light, but the variability of the light of Uranus itself. The observed range was 0.15 magnitude, and the period of $0^d.451$ agrees so well with the period of rotation as determined spectroscopically at the Lowell Observatory, that the fluctuation was assumed to be due to the rotation of the planet, different portions of whose surface are unequally bright.[5]

[2a] Mem. Amer. Acad., **8**, 221, 287, 1861; M. N. R. A. S., **21**, 197, 1861.

[3] H. A., **61**, Chap. 5, 1908.

[4] H. A., **59**, No. 10, 1912.

[5] H. C. 200, 1917.

Reflected sunlight has been studied not only by means of the planets and the moon, but also through observations of the zodiacal light and Gegenschein. Investigations on the appearance and nature of the zodiacal light were made by Arthur Searle for many years, beginning in 1877, but occasional observations had been made at the Observatory since 1840. The details of these observations, and a discussion of them on the theory that the light is caused by sunlight reflected from particles belonging to the solar system are given in Harvard Annals **19**, Part 2, 1893. Searle later published observations of the Gegenschein made by various observers, especially at Arequipa.[6] He also discussed certain luminous bands which in his opinion affect the appearance of the zodiacal light.[7]

The Solar Spectrum.—With the development of photographic methods, Edward C. Pickering included some work on the solar spectrum in the general study of spectral classification, paying special attention to the varying intensity of the atmospheric lines in the solar spectrum as affected by variations in temperature, moisture, and other meteorological conditions.[8] He also did pioneer work on line intensity for the spectral regions around the Fraunhofer line E,[9] and thus helped to pave the way for the future investigations of solar and stellar atmospheres.

Recently there has been a renewal of researches on line intensity in the solar spectrum, using the searching methods of spectrophotometric analysis recently developed at the Observatory. The sun, therefore, while not assiduously studied, is not absent from the Observatory's programs, and is kept constantly in mind as one of the stars.

The Moon's Brightness.—Work on the photometry of the moon was begun early, and also on that of other members of the solar system. George P. Bond, in 1860, presented to the

[6] H. A., 33, No. 2, 1900.
[7] *Ibid.*, No. 3.
[8] H. A., 48, No. 8, 1903.
[9] H. C. 72, 1903.

American Academy of Arts and Sciences two papers on this subject.[10] Bond's experiments, based in part on photographs made by Whipple with the large refractor, were pioneer efforts in photographic photometry and led to interesting results. They appeared to show that the moon absorbs about 10 parts out of 11 of the light that falls upon it; Jupiter, on the other hand, appeared to reflect, or at least to shine with, more light than falls upon it from the sun—that is, to be slightly self-luminous. This result for Jupiter has never been certainly confirmed. Bond found full moonlight to be 7.38 times as bright as half moonlight—a difference of 2.17 magnitudes—and only 1/471,000 as bright as the sun.

This value for moonlight was corrected by W. H. Pickering's observations made in Jamaica in 1900. He found the visual magnitude of the moon to be -12.50. Assuming this value and the corresponding magnitude of the sun, -26.83, the sun's light is about 540,000 times that of the full moon.[11]

As a part of his extended investigations into photographic photometry on a uniform scale, Edward S. King made a determination of the photographic magnitude of the moon at different phases. Photographs of the moon, having various exposures, were compared with standard squares formed by the light of an Argand lamp. King's results were derived from a study of nearly a hundred plates taken at all seasons and at different temperatures, careful attention being given to the effects of changes in temperature and humidity. A photographic magnitude of -11.20 was obtained for the light of the full moon, and of -9.01 for the half moon, a result which agrees well with the early determination of Bond. The photometry of the sun and moon presents many difficulties and is still a subject of investigation by Professor King.[12]

The Surface of the Moon.—In 1871, N. S. Shaler, Professor of Palaeontology at Harvard University, having previously

[10] Mem. Amer. Acad., **8**, 221, 287, 1861; M. N. R. A. S., **21**, 197, 1861.
[11] H. A , **61**, Chap. 5, 1908.
[12] H. A., **59**, No. 3, 1912.

had the moon under observation for several years, employed the large refractor on 35 nights in a study of the surface of the moon from the standpoint of a geologist. He came to the conclusion that all the contours of the lunar surface are the results of volcanic action, and that the radiating bands are crevices stained on their borders by escaping gases.[13] Similar views have been held by many selenographers, but the origin of the lunar markings is still in doubt.

During the years 1872 to 1874, the large refractor was used by Trouvelot, who made many elaborate and beautiful drawings of celestial objects, including details of the lunar surface. A number of these were published in Harvard Annals, **8**, Part 2, 1876. No more accurate representations of the surface of the moon were ever made before the perfection of photographic methods.

From his entrance into the Observatory in 1886 until the present time (1927), William H. Pickering has given much time to observations of the lunar surface. He early announced his rejection of the general belief that the moon is an entirely dead and waterless world, void of any atmosphere. His own observations, supported by those of other observers, indicated, in his opinion, considerable changes on the lunar surface, especially in the craters Plato and Linné. He even concluded that his observations pointed strongly to the existence of some form of lunar vegetation at the present time. He asserted the existence of a lunar atmosphere, and was convinced that his observations of Linné made during the total eclipse of October 16, 1902,[14] showed definite changes.

W. H. Pickering also prepared an atlas of the moon in 80 photographic plates. The visible surface of the moon was divided into 16 parts, and each of these is represented on five plates, one showing the region at lunar sunrise, one at sunset, and other plates at intermediate phases. The changes in the appearance of lunar features under varying illumination are

[13] H. A., **8**, 50, 1876.
[14] H. A., **32**, 1894; H. C. 67, 1902.

thus strikingly shown. Pickering was of the opinion that these photographs also show genuine physical changes in the lunar features, especially in the crater Linné; and he supplemented the photographs by elaborate drawings. The scale of all the plates is 5 seconds of arc to the millimeter. One of the most interesting features in connection with this research is the instrument with which it was undertaken. The photographs were made in the principal focus of a telescope having a lens of 12 inches diameter and 135 feet focal length. At that time it seemed uncertain whether such an instrument might not surpass telescopes of more usual construction in certain lines of photographic work. The moon appeared to offer the best test. In definition the results did not compare favorably with the best photographs of the day, and they are, of course, far surpassed by photographs made with the great instruments of later date. The experiment, however, was well worth a trial.[15] Much additional work has been done on the moon by W. H. Pickering.[16]

Lunar Eclipses.—The total lunar eclipse of January 28, 1888, was observed with three ends in view: observations of occultations of stars, desired by Struve; a study of the variations of actinic brightness; and, especially, a search for a possible lunar satellite. A theoretical determination of the probable size of such a satellite, its distance, and possible magnitude, was made by W. H. Pickering, but a search for it on several good photographs that were secured led to negative results. The conclusion reached was that no object so bright as the tenth magnitude could have escaped detection, and that the moon can have no satellite more than 200 meters in diameter.[17] Later attempts have been made to find a lunar satellite, but without success.

Eclipses of the moon may yield other observations of value, such as the occultations of faint stars, which may be used for

[15] H. A., **51**, 1903.
[16] H. A., **53**, No. 4, 1904; **61**, Chap. 8, 1908.
[17] H. A., **18**, No. 4, 1890.

determination of the dimensions and parallax of the moon. study of the earth's shadow, as projected on the eclipsed oon, may also contribute something toward a better knowledge ' the earth's atmosphere.

An extended investigation of the lunar eclipses between ;60 and 1922 has been made by Dr. Willard J. Fisher, in the ›pe of finding evidence of a structure of the earth's shadow ›rresponding to the known dust layers of the atmosphere. roof of such a relationship was not immediately obtainable, ıt a thorough study was made of the relative brightness of the :lipses. Fisher found that the position of the moon's path ith regard to the center of the shadow is significant; that the fect of volcanic dust is evident in the shadow on the moon; ıd that the atmosphere of the earth's northern hemisphere is ss transparent than that of the southern.[18] Dr. Fisher later scussed many observations of the total eclipse of the moon of ugust 14, 1924, which had a dark spot visible near the middle ' the shadow. The conclusion previously reached was ɜrified, that the atmosphere of the earth's northern hemisphere less transparent than that of the southern hemisphere.[19]

Determination of the Moon's Position.—The first .tempt to determine the position of the moon photographically as made by George P. Bond in 1857. Various attempts were ade later by European astronomers. In 1911 Edward C. ickering, in consultation with Ernest W. Brown of Yale niversity and Henry N. Russell of Princeton University, ıdertook further researches to this end. The success of the ıdertaking was largely due to Edward S. King, who perfected ıe apparatus and technique for obtaining suitable photographs. he measuring of the plates and the discussion of the results ere carried out by Professor Russell, or under his direction. ussell concluded that "the photographic method, at the first ial, gives results apparently somewhat superior in accuracy

[18] Smithsonian Miscellaneous Collection, 76, No. 9, 1924.
[19] H. C. 284, 1925.

to meridian observations of the highest class." Later measurements confirm this estimate of accuracy. Russell states that it is obvious from an inspection of the diagrams that the precision of the photographic observations is on the average at least fully comparable with that of the Greenwich meridian circle and greater than the altazimuth observations.[20]

The Observatory has not been and is not now equipped to compete in lunar photography with some other observatories; but it has played a worthy part in the early photometric work, in making accurate drawings, in investigating lunar geology, and in experimenting in the photography of the position and surface of the moon.

The Planets and Their Satellites.—Soon after the mounting of the large refractor in 1847, planetary observations were enthusiastically begun by the Bonds, especially on Saturn, its rings, and satellites. These were continued for about 10 years, and led to the discovery of Bond's Dusky Ring and the eighth satellite, Hyperion. Many other interesting observations of this system were made, notably at the times when the plane of the rings passes through the earth and the sun. Charles W. Tuttle and Sydney Coolidge took part in these observations.[21]

During the 20 years from 1857 to 1877, observations of the planets seem to have languished, except for George P. Bond's photometric work, and some micrometric measures of the satellites of Saturn, Uranus, and Neptune, made during 1866 to 1868 by Joseph Winlock, with the assistance of Benjamin Peirce, Charles S. Peirce, Samuel P. Langley, and George M. Searle.[22]

When Edward C. Pickering took up his duties as director, early in 1877, he turned his attention not only to the photometry of the stars, but also to the photometry of some of

[20] H. A., **72**, No. 1, 1911; **76**, No. 7, 1915; **80**, No. 11, 1917; **81**, No. 5, 1919; **85**, No. 9, 1926.

[21] H. A., **2**, Part 1, 1857.

[22] H. A., **13**, Chap. 4, 1882.

the planets and their satellites, and of some asteroids. The observations were made at first with the 15-inch refractor, but later different meridian photometers were devised. For use with the large refractor, photometers of special construction (chiefly of polarizing type) were employed, made for the most part under Pickering's supervision. Since much light is lost in a polarizing photometer, very faint objects (such as the satellites of Mars, which were discovered by Hall at about that time) must be observed without the intervention of any absorbing or reflecting media except those of the telescope itself. The satellites of Mars, therefore, were compared with a starlike image formed by passing the light of the planet through an extremely minute hole in a metal screen. A series of observations of Phobos and Deimos was made in 1877, and again in 1879, by Pickering, assisted by Searle, F. Waldo, and Wendell. The subject was of wide interest at that time. The positions of the satellites, also, were measured frequently, and data were thus furnished for improved orbits of the satellites, and more accurate determinations of the mass of Mars.[23] Observations in 1881 to 1882, made with an improved photometer, gave the mean magnitudes, 14.42 and 14.11, for Deimos and Phobos, respectively, and 13.13 for the magnitude of Deimos at mean opposition.[24]

At one time or another almost every form of photometer has been tried at the Observatory. A conjunction of the planets Mars, Saturn, Jupiter, and Venus, in 1877, afforded an opportunity to compare their relative magnitudes. No telescope was employed, as the light was sufficient with the photometer alone.[25] Photometric measures were also made of the satellites of Jupiter, Saturn, Uranus, and Neptune.[26] Observations of the planets and brighter satellites and minor planets were carried out also with the meridian photometers.[27]

[23] H. A., **11**, Chap. 7, 1879; **13**, Chaps. 5 and 6, 1882.
[24] H. A., **33**, No. 9, 1900.
[25] H. A., **11**, Chap. 3, 1879.
[26] *Ibid.*, Chaps. 8–10, 1879; **69**, Chap. 12, 1909.
[27] H. A., **24**, 265, 1890; **46**, Chap. 8, 1904.

The photographic magnitudes and color indices of Venus, Mars, Jupiter, Saturn, and Uranus have been more recently determined by King,[28] using the accurate out-of-focus methods described in Chapter XI.

Eclipses of Jupiter's Satellites.—An extensive and important research at the Observatory consisted in the observation of the precise times of eclipses of the satellites of Jupiter. The determination of these times presents special difficulties, for the satellites have sensible discs, and therefore the eclipse is not an instantaneous event, but has considerable duration. The time consumed by the satellites in entering or leaving the shadow of the planet varies in general from 4 to 13 minutes. Hence, with different observers and instruments, using ordinary methods of visual observation, the recorded times of eclipse differ by several minutes. To avoid this large element of uncertainty, Edward C. Pickering undertook in 1878 to determine by photometric means the moment when the center of the satellite enters or leaves the shadow. The light of the eclipsing satellite was usually compared with that of another satellite. Readings were rapidly made with a polarizing photometer from the beginning to the end of the disappearance, or reappearance. Such observations during a period of 25 years, 1878 to 1903, by E. C. Pickering, Searle, and Wendell form Part 1 of Harvard Annals, **52**, 1907. A discussion of these observations by Ralph Allen Sampson, Professor of Mathematics and Astronomy in the University of Durham, now Astronomer Royal of Scotland, was published two years later. Professor Sampson developed the theory of these eclipses, corrected existing theories, and discussed the Harvard observations. He came to the conclusion that various anomalies which were present were due to the departures of Jupiter's figure from a perfect spheroid, and that the departures are probably irregular and transient.[29] Additional visual observa-

[28] H. A., 59, No. 10, 1912; **85**, No. 4, 1923.
[29] H. A., **52**, Part 2, 1909.

tions of the eclipses were made by Wendell from 1903 to 1912, the year of his death.[30]

Photographic observations of the eclipses of Jupiter's satellites were made by Edward S. King from 1888 to 1898, with the 11-inch Draper refractor. He obtained many series of images of Jupiter and its satellites taken at intervals of 10 seconds. On plates thus taken the image of the eclipsing satellite gradually disappears or reappears, and the moment of half brightness can be determined. A comparison of the results of these observations with those of the visual photometric observations referred to above shows that in general for satellites I and II, the photographic determination of the time is somewhat later than the visual for disappearance, but earlier for reappearance. The fogging of plates by halation, due to the bright image of Jupiter, greatly increased the difficulties encountered in their reduction.[31] King also photographed several lunar occultations, including some of Saturn, by a somewhat similar method.[32]

Planetary Observations by W. H. Pickering.—For many years William H. Pickering has given much attention to planetary observations. At Arequipa, in 1891 to 1892, he undertook observations of an artificial disc, in order to determine, in ordinary observations of the planets, the errors due to irradiation, poor definition, and other causes. A large disc, 8 feet in diameter, on whose surface were painted black lines, dots, and crosses, was placed on the flank of Mount Chachani, at an altitude of about 16,600 feet, and at a distance of 11.25 miles. The results, however, were not altogether satisfactory, since the observations on the artificial disc were made in the daytime and were influenced by poor seeing and other conditions. Similar observations were later carried on at Cambridge. Many observations, too, were made by W. H. Picker-

[30] H. A., 69, Chap. 13, 1912.
[31] H. A., 80, No. 10, 1916.
[32] H. A., 59, No. 7, 1912.

ing and Douglass on the surface markings and other peculiarities of Mercury, Venus, Mars, Jupiter, and Neptune. Among the conclusions drawn from these observations were: the periods of rotation and revolution of Mercury must be nearly, or quite, equal, and the planet's atmosphere is extremely rare; the diameter of Venus was found to be 7662 miles, and her atmosphere is probably many times as dense as that of the earth. Pickering and Douglass observed no color in the atmosphere of Venus. The diameter of Neptune was found to be $2''.30$, a value somewhat less than that previously found by most observers, but in agreement with later determinations. The ellipticity of Jupiter's satellites also has received much attention.[33]

The Ninth Satellite of Saturn.—From an examination of Bruce plates made at Arequipa, William H. Pickering discovered in 1899 a ninth satellite of Saturn. This discovery was not an accident, but the result of a definite plan and long search. The name "Phoebe" was appropriately assigned to the new satellite by Pickering, thus adding the name of another member of Saturn's family. The orbit was found to be elliptical, and a study extending over several years revealed the fact that the motion of the satellite is retrograde. This was unexpected at that time, but later the motion of two of the outer satellites of Jupiter, discovered by Perrine, was also found to be retrograde. Pickering also found certain extremely faint images on the Bruce plates, which he attributed to the presence of a tenth satellite of Saturn. To this object he gave the name "Themis." The reality of the tenth satellite, however, has never been confirmed elsewhere, and until this is done by an independent investigator, the existence of Themis must be considered doubtful.[34]

The Surface of Mars.—Many observations have been made, and numerous papers written concerning the surface

[33] H. A., **32**, Chaps. 4 and 5, 1900; **61**, Chap. 6, 1908; **82**, No. 4, 1923.
[34] H. A., **53**, Nos. 3, 5, 6, and 9, 1905; **60**, No. 3, 1908; **61**, Chap. 7, 1908.

markings and physical conditions of the planet Mars, by W. H. Pickering. The greater part of this work has been published in astronomical journals, especially in Popular Astronomy. Several investigations, however, appear in the Annals; one, on Martian Meteorology, is a study of the temperature, cloudiness, seasonal changes, and atmospheric circulation, based chiefly on photographs of the planet made at Arequipa in 1888 and 1890.[35] Many determinations of the positions of various points on the surface of Mars were made during the oppositions of 1914, 1916, 1918, 1920, and 1922. On these were based the paper "Location of a Hundred Points on the Planet Mars." It is illustrated by a map showing the positions of the well-determined points.[36]

The Transneptunian Planet.—W. H. Pickering undertook to investigate by graphical methods the evidence in favor of the existence of a transneptunian planet. The possible existence of such a planet had been in the minds of astronomers for a long time, and several attempts had been made to discover it. After a preliminary discussion of the perturbations caused by Neptune on Uranus, Saturn, and Jupiter, Pickering considered the perturbations caused on Uranus and Saturn by some unknown planet, and the influence of such a planet on Neptune. Elements were derived for the unknown transneptunian planet, which he designated by O.[37] Two years afterward he located, by means of cometary statistics, three other planets exterior to it; he believed them to be extremely massive and very remote.[38]

A revision of these results, made several years later, gave a summary of similar researches made by other astronomers. Revised elements for Planet O were derived, but an examination of photographic plates gave negative results. Similar examinations elsewhere had no better outcome. If such a planet

[35] H. A., 53, No. 8, 1905.
[36] H. A., 82, No. 5, 1924.
[37] H. A., 61, Part 2, 1909.
[38] H. A., 61, Part 3, 1911.

exists it is doubtless rather faint, perhaps of the twelfth magnitude or fainter. Had it been as bright as the eighth or ninth magnitude, it could hardly have escaped detection so long.[39]

The Asteroids.—Occasional observations of asteroids have been made by members of the Observatory since 1866. During Winlock's administration, the positions of a number of asteroids were determined.[40] In 1877, E. C. Pickering, assisted by Searle and Upton, began photometric observations of the brighter asteroids in connection with the photometry of the stars,[41] and photometric observations were made with the Meridian photometer from 1882 to 1888.[42]

Henry M. Parkhurst of New York, in association with the Observatory, made a valuable contribution to the photometry of asteroids in 1887 and 1888. His long series of photometric observations were of special interest in showing the relation of phase to brightness.[43] Searle found that these results had an important bearing on his discussion of the brightness of the zodiacal light and Gegenschein.[44] Parkhurst continued his observations until 1889,[45] and E. C. Pickering's conclusions based on Parkhurst's measures compared well with those obtained in Germany by Müller. Both found independently, and by different methods, that the effect of the phase upon the magnitude of an asteroid is sensibly proportional to the angle determining the phase, an unexpected law of variation, conforming to no theory that had been proposed.[46] These conclusions were confirmed by observations made with the large refractor by Searle and Wendell.[47]

[39] H. A., **82**, No. 3, 1919.
[40] H. A., **13**, Chap. 7, 1882.
[41] H. A., **11**, Chap. 12, 1879.
[42] H. A., **24**, 264, 1890.
[43] H. A., **18**, No. 3, 1890.
[44] H. A., **19**, 235, 1893.
[45] H. A., **29**, No. 3, 1893.
[46] *Ibid.*, Appendix.
[47] H. A., **33**, No. 1, 1900.

Several new asteroids have been discovered on the Harvard photographs, and doubtless others, not yet noticed, are present on the plates, besides many trails of known asteroids. Ocllo, (475), discovered at Arequipa in 1901 by Stewart on a Bruce plate, is an especially interesting object. The inclination of its orbit is considerable and the eccentricity is larger than that of any asteroid known at that time.

Reverend J. H. Metcalf, in his private observatory, which was long associated with the Harvard Observatory, discovered several new asteroids with photographic telescopes of his own construction.

Variability of Eros.—Eros, (433), though small in size, is in many ways the most interesting of the asteroids. It was discovered in 1898 by Witt. At times it comes nearer to the earth than any other known celestial body except the moon. Such times, however, are rare. One occurred in 1894, four years before the discovery of Eros. Fortunately, its path in 1893 and 1894 became well known from an examination of the photographs in the Harvard collection. An accurate determination of its orbit was thus possible without delay. At times of close approach, the parallax of Eros, and hence indirectly the parallax of the sun, can be determined with a high degree of accuracy.[48]

Early in 1901, Oppolzer announced the variability of the light of Eros, which was promptly confirmed by several observers. It was found to have a period of about five hours, or perhaps one-half that length. Wendell found that its range of variation was 1.1 magnitudes on March 12, 0.4 magnitude on April 12, and less than 0.1 on May 6.[49]

During the opposition of 1903 to 1904, systematic photometric observations of Eros were made at Arequipa by S. I. Bailey. Both visual and photographic methods were employed. The variations in light were clearly shown by the visual observa-

[48] H. A., **53**, No. 10, 1905; H. C. 34, 1898; 36, 1898; 37, 1899; 51, 1900.
[49] A. N., **155**, 309, 1901.

tions, and were amply verified by the photographic observations on Bruce plates. The double period, 0.2196 day, was found to satisfy all the observations. The range of variation appeared to change slowly and uniformly, during the time covered by the observations, the range varying from one-half to three-quarters of a magnitude. Photometric observations were also made of 22 other asteroids, five of which showed evidence of variability.[50]

Investigations on the light curve of Eros in 1914 were made by Margaret Harwood, Director of the Maria Mitchell Observatory. From an examination of all available data, including photographs made at the Harvard, as well as at the Maria Mitchell Observatory, she found a variation of about 0.3 magnitude in the light of Eros, and an apparent period of $0^d.3064$ instead of $0^d.2196$, as previously found.[51] Later Miss Harwood made an exhaustive summary of all the data in regard to Eros and other variable asteroids, and discussed theories in regard to the variations.[52]

Discovery and Observation of Comets.—The establishment of the Harvard Observatory on a sound foundation was due, as shown elsewhere, to the deep public interest in the great comet of 1843. Indeed, there has always been a popular demand for information in regard to new or brilliant comets. It was natural, therefore, that the early members of the Observatory staff should give them considerable attention. Altogether, a number of new objects were discovered; and much time has been spent in their observation, and in the computation of orbits. George P. Bond's monograph on Donati's comet of 1858, a work which has been called an astronomical classic, contains many elaborate drawings and diagrams of the physical appearance of the head and tail of the comet, and a large collection of data from various sources.[53] Comets were the

[50] H. A., **72**, No. 5, 1913.
[51] H. A., **76**, No. 8, 1915.
[52] H. C. 269, 1924.
[53] H. A., **3**, 1862.

first occasion for the astronomical telegraph service, for which the Observatory became the center.

For many years, beginning about 1880, a large amount of volunteer work was done by Seth C. Chandler, a remarkably rapid computer, who would carry through the computations necessary to the announcement of the elements of a new orbit, with little or no regard for rest or sleep. Similar work was later carried on by Wendell. Observations of comets were made by Winlock, C. S. Peirce, G. M. Searle, and Wendell, during the years 1867 to 1881.[54]

A study of Comet Swift, 1892, was made by W. H. Pickering from photographs taken at Arequipa with various instruments. From an examination of these photographs Pickering concluded that the comet revolved about a longitudinal axis in a period of about four days. He also drew attention to the "electrical nature of the phenomena exhibited," and made a detailed comparison of these phenomena with terrestrial auroras.[55]

Photometric observations of the intensity of the light of different parts of several comets, which appeared from 1879 to 1893, were made by E. C. Pickering, Searle, and Wendell.[56]

A statistical investigation of nearly 500 comets and reappearances of comets, which have been well observed during the last 2000 years, was made by W. H. Pickering. The orbits of these comets were classified in different ways, and Jupiter's "family" of comets was discussed. When the comets are classified according to their aphelion distances, the influence of an unknown planet, Q, beyond Neptune, is indicated. Mr. Pickering explains "how we may compute the distance, eccentricity, and longitude of perihelion of a planet that has never been seen." To explain the various groups of comets, planets P, Q, and R are assumed, as well as a transneptunian planet, O. A photographic search for Planet O was made in 1911 with negative results.[57]

[54] H. A., **13**, Chap. 8, 1882.

[55] H. A., **32**, Chap. 10, 1900.

[56] H. A., **33**, No. 8, 1900.

[57] H. A., **61**, Part 3, 1911.

CHAPTER VIII

TERRESTRIAL PROBLEMS

As part of its work on members of the solar system, the Observatory has carried on researches on the earth in its relation to the rest of the celestial bodies. These researches have fallen into four groups: studies of meteors in their paths through the upper atmosphere of the earth; meteorological studies of the lower atmosphere; work on terrestrial magnetism; and geodetic work for the accurate location of positions on the earth's surface.

The Study of Meteors.—No systematic study of meteors was undertaken for many years after the foundation of the Observatory. Occasional notes occur, however, in the records of different observers regarding the appearance of especially brilliant meteors, or fireballs, which could not fail to attract attention. The most famous of these was the fireball of September 30, 1850, which was seen by Jenny Lind as she sat at the eyepiece of the new 15-inch refractor. This meteor was also observed by William Mitchell at Nantucket and by many others.[1]

From 1884 to 1888, O. C. Wendell published in the Sidereal Messenger computations of radiant points from which meteors following the orbits of known periodic comets should appear at certain dates. Similar papers by him appeared in the Astronomische Nachrichten in 1886, in Astronomy and Astrophysics in 1892, and in Popular Astronomy in 1908. In several cases an intimate relation was shown to exist between the orbits of meteors and known comets.

[1] Annual of Scientific Discovery, 1851.

The Leonid shower had become conspicuous from its brilliant apparitions in 1833 and 1866. E. C. Pickering was active in promoting a systematic study of its return in 1899. Its appearance in 1833 had been a most striking exhibition, and although it was somewhat less so in 1866 and 1867, a brilliant spectacle was expected in 1899. As showers, however, might occur one or two years earlier or later, the program was arranged to begin in 1897 and cover the period 1897 to 1899. A comprehensive scheme of observations was made out, a map of the region of the Leonid radiant was prepared, and the cooperation of observers in all parts of the world was secured. The work of 1897 was both visual and photographic; members of the Observatory occupied stations at Cambridge and on Blue Hill, and 138 meteors were observed. The results were discussed in the Harvard Annals by W. H. Pickering.[2]

The work at the return of the shower in 1898 was largely photographic. On November 14, 96 photographs were taken at Cambridge with the Draper 11-inch equatorial and with 11 smaller instruments. Two cameras were taken to Tufts College, and 25 simultaneous photographs were taken at both stations. In all, 34 trails of 11 different meteors were photographed—a remarkable collection of data for a single night's work.[2a] Attempts to photograph the spectra of these meteors failed.[3]

Extensive preparations were made for the expected return of the Leonids in November, 1899. The world-wide organization of observers was complete, and at the Observatory preparation was made for both visual and photographic observations. The Leonids, however, failed to appear in considerable numbers, and no results deemed worthy of publication were obtained.[4] In the years immediately following, comparatively few meteors

[2] H. A., **41**, No. 5, 1902; H. C. 31, 1898.

[2a] The Harvard data have only recently been discussed by Dr. Fisher in Harvard Bulletin 870, 1930. The data obtained at Tufts College are still unpublished.

[3] H. C. 35, 1898; 40, 1899.

[4] H. C. 45, 1899.

appeared in Cambridge although observations were made in 1901 and 1904.[5] Rather brilliant Leonid showers, however, were reported from other parts of the world.[6]

W. H. Pickering contributed occasional articles in later years on meteors and meteor theory to the Astrophysical Journal and to Popular Astronomy, and took an important part in the discussion of the "meteoric procession" of February 9, 1913. This remarkable event was observed from Saskatchewan to the South Atlantic, and was caused by a long, narrow swarm of bright meteors which followed an apparently curved path through the upper atmosphere at heights which seemed to change little in all that long journey.[7]

Occasional meteor trails occur on the astronomical photographs in the Harvard collection. These plates were generally taken as stellar charts or spectrum plates, and the meteor trails are fortuitous. During the years while Mrs. Fleming was busied with the examination of these plates, she made a record of 91 meteor trails and four meteor spectra. Some of these were placed on exhibition as illuminated transparencies. The first systematic examination of any of the Harvard plates for the special study of meteors, however, appears to have been begun in 1922 when Miss Ames and Miss Howarth, under Dr. Shapley's direction, undertook an examination of 2000 plates made with a Cooke lens of about one inch aperture, having exposures of one hour. More exactly, the 2000 plates had a total exposure of 2297 hours. Four sets of regions and time intervals were so chosen that each included the radiant point and date of a known meteor shower. The total number of meteors found was 24, "indicating the great rarity of meteors sufficiently bright for detection by the patrol telescopes as ordinarily used in charting stars to the eleventh magnitude."[8]

[5] H. C. 89, 1904.

[6] Pop. Astr., 10, 400, 1902.

[7] Pop. Astr., 30, 632, 1922; 31, 96, 443, 501, 1923. A recent rediscussion of the data by Dr. W. J. Fisher, published in Harvard Reprint 47, 1928, interpreted all the observations satisfactorily for the first time by taking into account the equatorial rotation and bulge of the earth.

[8] H. B. 788, 794, 1923.

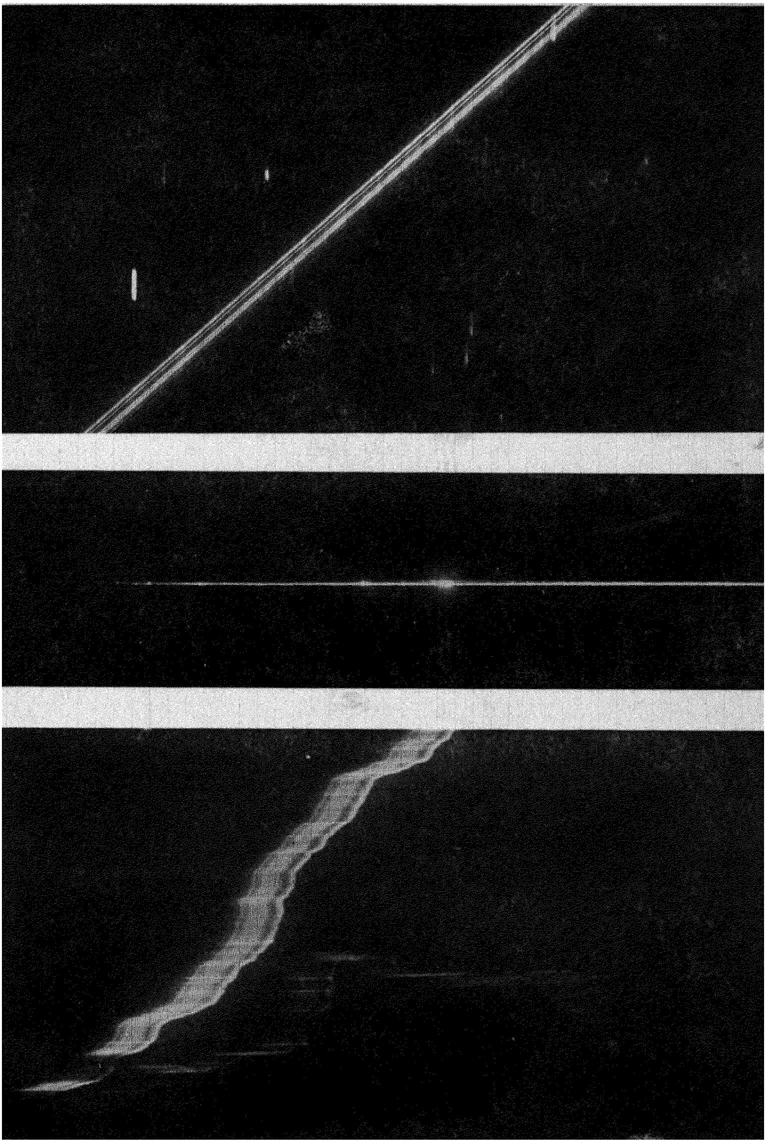

PLATE XI.—(Top) SPECTRUM OF A METEOR. (Photographed with the Bruce Telescope.) (Middle) MULTIPLE METEOR TRAIL. (Bottom) SPECTRUM OF LIGHTNING.

(Facing page 98)

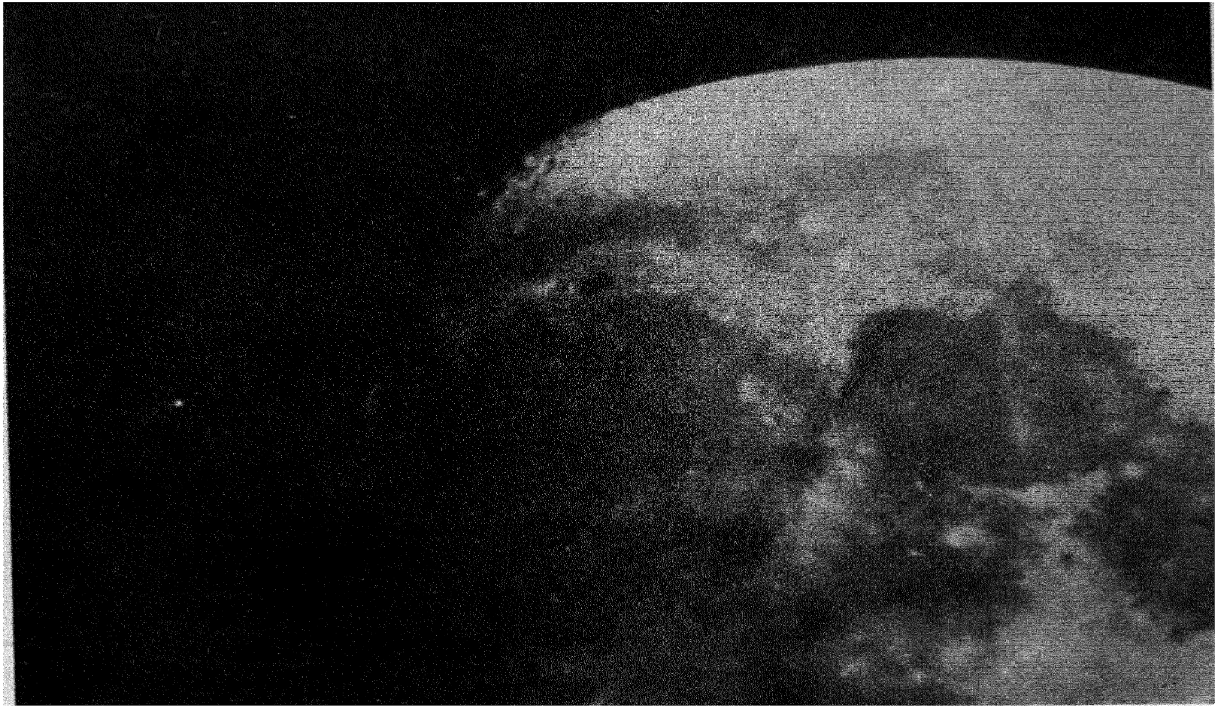

PLATE XII.—EARLY PHOTOGRAPH OF LUNAR OCCULTATION. (*See page 117.*)

At about the same time King determined the Orionid radiant very exactly from three trails found on a single plate. A parabolic orbit for the Orionid meteors was also computed by the method of Bauschinger, using the 1900 and 1922 positions of the radiant.[9]

In 1925, a grant for meteor work at the Observatory was made by the J. Lawrence Smith Fund Committee of the National Academy of Sciences. Under this grant work was undertaken by Dr. Willard J. Fisher, and is still in progress. Some account of its scope is indicated in the following summary.

a. Discovery, Measurement, and Study of Meteor Trails on the Harvard Plates.—An examination of 71,454 plates made with different instruments yielded 213 meteor trails. The total number of such trails is now known to be at least 360; another illustration of the rarity of such trails on photographic plates of the sky—a result of the rapid motion of the meteors. But the photographic data compensate for their fewness by their accuracy; each is an authentic record of an air path; and knowledge of meteors is largely based on air paths.

b. Promotion of the Study of Fireballs.—Interest in fireballs is aroused by the circulation of questionnaires in the daily press and by radio, whenever any notable fireball of the sort is reported and by subsequent popular publication of the results; the answered questionnaires received from numerous amateur observers are studied and discussed and the results are published and circulated in the scientific press and as abstracts in the daily papers. Among the phenomena which were thus handled at the Observatory were the fireballs of November 15 and December 29, 1925, and August 10 and October 16, 1927.

c. Theoretical and Critical Study of Meteoric Problems.—Attempts are made to promote the gathering of precise photographic data on the air paths of meteors. Only thus can the evanescent changes in the air paths be recorded for measurement, or spectrum records be obtained, so essential for the understanding of the physical processes which accompany the

[9] H. B. 778, 1922; 783, 1923.

destruction of one of these solids. Photography cannot replace the eye in meteor observations, but the two methods supplement each other.[10]

Meteorology.—One result of the assiduous study of meteors will be the increased knowledge of the upper atmosphere. The lower atmosphere, within reach of our recording instruments, is still a problem which astronomers must take into consideration. In seeking sites for astronomical observing stations long series of meteorological observations are needed. At the present time there is an abundance of independent meteorological observatories or stations. A century ago, however, such separate observatories were rare, and meteorological observations were often undertaken by astronomical observatories, including the Harvard Observatory as a logical part of their work.[11]

Extended meteorological observations were early undertaken at the Dana House Observatory. So important did this line of investigation appear to the first director, William C. Bond, that in his Annual Report for 1849 he made the following statement:

> It has for a long time been a subject of regret among those interested in meteorology and terrestrial magnetism, that there was not within the limits of the United States a single regularly organized Meteorological Observatory, where a continued and systematic course of observation was pursued, such as might serve for a point of departure whence differences might be reckoned, and where instruments intended to be used on surveys and explorations might be verified by standards indicating the momentary condition of the atmosphere and the magnetism of the earth. We are now in a condition to furnish all the instruments required for such an establishment, and need only a suitable building for their accommodation, such as would be afforded by the erection of the western wing of our Observatory, according to the original design.[12]

[10] H. B. 845, 849, 852, 853, 1927; 854, 1928; Pop. Astr., **34**, 421, 1926; Proc. Nat. Acad. Sci., **12**, 728, 1926; **13**, 540, 578, 1927; Journ. R. A. S. Can., **20**, 225, 1926; Science, **64**, 507, 1926; **66**, 507, 1927.

[11] See pp. 18, 34.

[12] H. A., **1**, cxxxix, 1856.

The plan of establishing an associated meteorological observatory was never completely carried out; nevertheless, systematic meteorological observations were made in Cambridge for nearly half a century.[13] Later, the establishment of the closely associated Blue Hill Meteorological Observatory rendered unnecessary a continuance of laborious meteorological observation at the Cambridge Observatory. Until 1888 the data were collected continuously. They were reduced and discussed by Arthur Searle, and were published in the Annals, together with notes on auroras and thunderstorms.[14]

The Blue Hill Meteorological Observatory was founded by A. Lawrence Rotch in 1885, as a private institution. It soon became one of the best equipped meteorological stations in the United States and its relation to the Harvard Astronomical Observatory was very intimate. After its establishment it became apparent that the Harvard Astronomical Observatory could be of greater service to science by undertaking the publication of the Blue Hill results than by an extension of its own meteorological work. An arrangement was therefore concluded by which the Blue Hill observations appeared in the Annals of the Astronomical Observatory of Harvard College. Rotch became a member of the Harvard staff, and the ultimate union of the two institutions was contemplated. On the death of Mr. Rotch in 1912, however, the Blue Hill Meteorological Observatory, which he had left by will to the University, was made a separate department by the Corporation. Nevertheless, from 1889 to 1927 ten volumes of the Annals were devoted to the results obtained at the Blue Hill Meteorological Observatory. These included, in addition to the usual tables of meteorological observations, a large variety of papers discussing different phases of the science.[15]

[13] Partial reports: Mem. Amer. Acad., 1846; American Almanac, 1844 to 1857; Patent Office Reports, 1856 to 1859.

[14] H. A., **19**, Part 1, 1889.

[15] H. A., **20**; **30**; **40**; **42**; **43**; **58**; **68**; **73**; **83**; **86**, Parts 1, 2, and 4; **87**, Part 1.

For the further encouragement of meteorological science, cooperation was established with the New England Meteorological Society in the publication of its results during the years 1888 to 1895,[16] and the observations of the United States Signal Service on the summit of Pikes Peak, Colorado (altitude 14,134 feet), from 1874 to 1888 were also published by the Observatory.[17]

In 1887, under the Boyden Fund, extensive series of meteorological investigations were undertaken for the purpose of determining the best site for an astronomical station, either in the northern or southern hemisphere. Personal visits were made to Colorado and California, and correspondence was opened with the officials of the Central and Southern railways of Peru, which reach high altitudes. After the establishment of the Boyden Station at Arequipa, Peru, regular meteorological observations were maintained from 1891 to 1927. In addition to the observations at Arequipa, a number of secondary meteorological stations were maintained for several years, extending from Mollendo on the Pacific Ocean over the western Andes to the Titicaca Plateau, and beyond the eastern Andes to Santa Ana in the valley of the Urubamba River. This line of stations reached its highest point at the station established in 1893 on the summit of El Misti, at an elevation of 19,200 feet. The results obtained at these stations constitute an important contribution to meteorology in a region where few observations had previously been made, and at altitudes seldom if ever attained.[18]

Terrestrial Magnetism.—Isolated though important observations in terrestrial magnetism had been made for several centuries, but the subject was first made international and handled in a strictly scientific manner only a few years before the foundation of the Harvard Observatory. Humboldt erected the first magnetic observatory at Berlin in 1828.

[16] H. A., 21; 31; 41, Nos. 1–4.
[17] H. A., 22.
[18] H. A., 39; 49; 86, Part 3.

In 1833 Gauss, in his theoretical study of the earth's magnetism, finding his progress stopped by the want of accurate and extensive data, founded a magnetic observatory at Göttingen. A little later Humboldt asked aid of the Royal Society of London, which made an appeal to the English-speaking world for more extended observations. This appeal was answered by the magnetic observatory in Philadelphia and by the recently established Observatory at Cambridge. A suitable equipment of magnetic instruments was provided through a grant of the American Academy of Arts and Sciences.

The scheme of simultaneous observations first arranged by the Royal Society for the different stations was designed to cover the three years 1840 to 1842. Work was begun at the Dana House Observatory in March, 1840, with the Gauss magnetometer of Mr. Bond; and later the observations were extended to the three newly arrived magnetometers provided by the American Academy. The observations were continued until March, 1843.

The plan of the Royal Society prescribed that the declination magnetometer and the horizontal and vertical force instruments should each be observed once every 2 hours during the 24 hours on every day of the year. One day in each month was set apart for observations with the three instruments at shorter intervals. On these days, called "term-days," the declination magnetometer was to be read every 5 minutes and other instruments every 10 minutes, making in all 576 observations during the day. All these observations were made by volunteer observers. The death of William C. Bond, Jr., in 1841, increased the difficulties encountered in securing such continuous observations without paid assistants. During some of the period, the work was superintended and the results discussed in part by Professor Lovering, assisted by Professor Benjamin Peirce.[19] During this period also the student members of "The Meteorological Society of Harvard University," assisted in the work at the Observatory,

[19] Mem. Amer. Acad., New Series, 2, 1, 85, 1846.

which included a time service and detailed meteorological observations. The observations showed the extreme complexity of the magnetic variations, the small diurnal range in declination and its irregularities, and the effects of solar cycles, and auroras.

Additional observations for a second period of years were proposed by the Royal Society. Owing, however, to the engrossing nature of the observations, the lack of paid assistants, and the press of other work, Mr. Bond was forced to decline participation in a second campaign at that time, and such observations have never again been taken up at the Observatory. America, however, has made large contributions to the study of terrestrial magnetism, especially by the many and widely separated stations of the United States Coast and Geodetic Survey, and by the work of the Carnegie Institution under the direction of Dr. L. A. Bauer.

Geodesy.—During its early years, the Observatory was closely associated with geodetic work. Both before and after his connection with the Observatory, William C. Bond was in official relation with the United States Coast Survey. At that time, Boston, that is, the "Cambridge Observatory," was generally regarded as the best determined position in America, and the center to which other positions were referred. The report of the Visiting Committee for 1856, under the chairmanship of Robert C. Winthrop, stated that:

> . . . it may be understood from various papers contained in the Reports of the Superintendent of the Coast Survey that the longitude of all the principal positions in the United States are dependent on the longitude of the Harvard Observatory.[20]

The accepted longitude of Harvard was not based upon the recent chronometer expeditions, but depended primarily upon the long and careful series of longitude determinations made by William C. Bond by observations of eclipses, transits,

[20] H. A., 1, clxxxiv, 1856.

occultations, and moon culminations. The reliability of these results had been appreciated as early as 1845 by the American and British Commissions in charge of the Survey of the Northeastern Boundary, which made use of Bond's results. His value of the longitude was only slightly modified by the chronometer campaigns of 1849, 1850, 1851, and 1855, and only slight additional modifications in the position of the Observatory have resulted from more recent determinations of the longitude by the telegraph and by radio.

The longitude of the Sears Tower, West of Greenwich, as determined by Bond's long series of observations and by many chronometer expeditions, was $4^h\ 44^m\ 30^s.7$. The following differences in longitude were derived from the Massachusetts and United States surveys:

	East of Sears Tower
The Observatory at Dorchester	$14^s.776$
The Observatory at Dana House	3.098
Cupola of State House, Boston	15.525

In 1844 and 1845 Colonel James B. Graham, Chief Astronomer and Surveyor of the Northeastern Boundary Commission, participated with the Bonds in the determination of the latitude of the new Observatory.[21] The latitude of the Sears Tower was north $42^\circ\ 22'\ 48''.1$. The following differences in latitude were also derived from the Massachusetts and United States surveys:

	South of Sears Tower
The Observatory at Dorchester (W. C. Bond)	$3'\ 37''.49$
Old Observatory at Dana House	31 .82
Cupola of State House, Boston	1 23 .89

The present accepted values of the latitude and longitude of the Sears Tower are:

Latitude $+42^\circ\ 22'\ 47''.6$; longitude $4^h\ 44^m\ 31^s.05$.[22]

After the position of the Observatory had been determined with all possible precision, less attention was given to geodetic problems. The Observatory has always been ready, however,

[21] Benjamin Peirce, Mem. Amer. Acad., New Series, 2, 183, 1846.
[22] H. A., 1, xvii, 1856.

to cooperate in geodetic work. For instance, in 1888, when Professor Mary E. Byrd desired to determine the longitude of the Smith College Observatory at Northampton, Massachusetts, the use of the Russian Transit, sidereal clock, and chronograph was extended to her. Corresponding instruments were used at the Smith College Observatory. Miss Byrd was assisted by Professor Mary W. Whitney, of Vassar College. Telegraphic signals were exchanged between the two stations on six nights, the observers exchanging stations after the third night. The position of the Russian Transit, as determined at that time, was $4^h 44^m 31^s.033$. The difference in position between the Russian Transit in Cambridge and the Smith College Observatory was found to be $+6^m 2^s.063$, giving $4^h 50^m 33^s.096$, as the longitude of the latter station.[23]

The latitude and longitude of the Boyden Station of the Observatory at Arequipa, Peru, was determined in 1896 to 1897, under Professor Winslow Upton, by the regular staff of the station as described in Chapter V. The determination of the latitude was made by transits in the prime vertical, using the Rogers Transit of the Arequipa Station. The mean result of observations made on several nights was $-16° 22' 28''.0$. A preliminary determination of the longitude was first made by moon culminations, as well as by a partial solar eclipse, and by a chronometer carried from New York to Arequipa in July, 1896. The means of the three methods gave a provisional value of $4^h 46^m 12^s$.

Difficulty was encountered in obtaining the necessary telegraphic connection between Arequipa and Arica by the land route, and the cable from Mollendo was used instead. This required the use of a relay at Mollendo, where the necessary duties were performed by Mr. Clymer.

At Arica the longitude of the church spire, la Iglesia Matriz is $4^h 41^m 19^s.991$, as determined by Lieutenant Commander Davis. The transit pier used by Upton was near the church.

The results of the campaign gave:

[23] H. A., 29, No. 2, 1893.

Longitude transit pier at Arica, West of Greenwich	4^h	41^m.	$19^s.90$
Difference in longitude of Arica and Arequipa		+4	51 .83
Longitude of Arequipa, transit instrument.........	4	46	11 .73

Professor Upton also made a determination of the altitude of the Boyden Station above sea level, by the use of the railway survey and the measured difference in altitude between the railway at Arequipa and the Boyden Station. The resulting altitude is 2451.4 meters, or 8043 feet.[25]

At the request of the Canadian Government, a longitude campaign between the Ottawa and Harvard Observatories was conducted in 1905 by Dr. Otto Klotz, at that time in charge of the Canadian Survey. The important series of longitude determinations carried on by the Canadian Government, extending completely around the world, was thus connected with the extensive system in which the Harvard Observatory has been a part. A small transit building was erected for this work after consultation with Dr. Klotz and the Superintendent of the United States Coast and Geodetic Survey. This shelter has remained as a permanent feature of the Observatory grounds, and has been found useful by officials of the government in later investigations.

[25] H. A., **48**, No. 9, 1903.

CHAPTER IX

ASTRONOMY OF POSITION

ASTROMETRY, the astronomy of position, was at one time the main concern of nearly all astronomical observatories. The chief interest of astronomers was centered on the movements and influence of the sun and planets, and the positions of the "fixed" stars were needed as points of reference; or, if the stars were not fixed, then their motions also were required in order to determine their precise positions at any time. Although astrophysics, leading the way to stellar evolution and other cosmic problems, has usurped the leading place in interest today, astrometry still plays an important rôle. It has occupied a prominent place in the work of the Harvard Observatory since its foundation to the present time.

The Bond Zones.—Owing to lack of suitable instruments, few observations for precise positions of the stars were undertaken with meridian instruments until the arrival of the 8-inch meridian circle obtained by Winlock in 1870. The chief work in astrometry during the early years of the Observatory was the observation of the faint stars in the zone from declination $0° 00'$ to $+1° 00'$. The observations were made with the 15-inch equatorial refractor, and were begun by George P. Bond in 1852 and carried out with the assistance of C. W. Tuttle, Safford, and Coolidge. A few observations were made by W. C. Bond. The recorder was usually Tuttle during the years 1852 to 1859, but during the remainder of the period 1859 to 1861 Asaph Hall was recorder.

The methods of observation need a brief explanation. A very thin sheet of mica, through which the stars were readily seen, was placed in the focus of the telescope. A series of lines

were engraved on the mica, dividing the field of the eyepiece in declination into 66 equal divisions, each having a value of 10″. Perpendicular to these were two lines so spaced as to represent 4^s at the equator. Each series, or zone, consisted of the stars in about two hours of right ascension, and 10′ in declination. After the zero of right ascension had been determined, the telescope was firmly clamped and remained fixed in position until the conclusion of the zone. The stars to be observed, which on the average entered the field of view at the rate of about two a minute, were observed as they trailed through the field. The declination of a star could be estimated readily to the nearest second of arc, and the observation was recorded by an assistant. The transits of the star across the vertical lines gave the position in right ascension, and were recorded on the chronograph, at that time a newly completed device not in general use. Each star was usually observed on two nights. An extended account was given by Bond of the methods and formulae employed in the reduction of the observations. Standard stars were selected from all the lists available; the zones, however, contained about 14 new stars to 1 standard star. These zones were published in three parts, the first containing stars from the equator to declination $+0° 20'$ the second, from $+0° 20'$ to $+0° 40'$, and the third from $+0° 40'$ to $+1° 00'$. In all, the zones contained over 16,000 stars,[1] of which about 2000 were duplicates.

The above zone observations were made between the years 1852 and 1861. In 1912, Professor Pickering and Miss Harwood, recognizing that this material offered an unusual opportunity for the determination of the proper motions of faint stars from visual observations, prepared a plan for reducing all the measures to a homogeneous system. The Nicolajew zone of the Astronomische Gesellschaft contains 1756 stars of the Bond catalogues, and the positions are more accurate than those available to Bond. Pickering and Miss Harwood reduced the Bond observations to accord with the more precise positions,

[1] H. A., **1**, Part 2, 1855; **2**, Part 2, 1867; **6**, 1872.

and carried them all forward to the epoch 1875.0. The new positions, therefore, are those of the dates of observation, so far as the proper motion is concerned, but reduced to the system of the Nicolajew Catalogue.[2]

Transit Observations.—A small transit instrument was mounted in the east wing in 1848 by W. C. Bond. This instrument had apparently received some injury during shipment which made it unreliable for observations in declination. It could be used, however, for determinations of right ascensions, and was so employed by Safford, who observed a catalogue of standard Polar stars and clock stars for the reduction of observations in right ascension. Safford also observed a list of 505 stars in right ascension during the years 1862 to 1865.[3]

Micrometric Measures.—Many observations of position were made with a large filar micrometer attached to the 15-inch telescope between the years 1866 and 1872, and similar observations were occasionally made until 1882. These investigations included double stars, nebulae, satellites, asteroids, comets, and occultations by the moon. The chief observers were Winlock, G. M. Searle, and C. S. Peirce.[4]

Meridian Circle.—The large meridian circle, described in Chapter IV, was received early in 1870. Transit observations were begun on November 10 of the same year by Rogers, who was placed in charge of the instrument. The early plans for work were formed by Winlock, but the observations, their reductions, and the discussion of the results were due to Rogers. The chief undertaking for many years was the observation and reduction of the zone between the limits $+49^\circ\ 50'$ and $+55^\circ\ 10'$, the part assigned to the Harvard Observatory by the Astronomische Gesellschaft in their plans for the revision of the northern Durchmusterung. While

[2] H. A., **75**, Part 1, 1912.
[3] H. A., **4**, Part 1, 1863; Part 2, 1878.
[4] H. A., **13**, Part 1, 1882.

the observation of the Gesellschaft Zone was, perhaps, the chief object to be attained, it was by no means the only investigation carried on during the years necessary for its completion. Begun in 1870, the observations of Rogers and his assistants were largely completed by 1879, but their final publication was not finished until 1896. Rogers resigned his position at the Observatory in 1886 to accept a professorship at Colby College, but he continued to supervise the reduction and preparation for publication of his observations. Chief among Rogers' assistants were Mr. Augustus McConnel, and Mr. J. F. McCormack, principally in recording, and Miss R. G. Saunders, Miss Anna Winlock, Miss S. C. Bond, Mr. W. Upton, and Mr. W. V. Brown, in the work of reduction.

The Catalogue of the Gesellschaft Zone is found in Harvard Annals, **15**, Part 2. It gives the precise positions of 8627 stars between $+49^\circ\ 50'$ and $+55^\circ\ 10'$. The determinations are differential. The primary stars which were employed in the reduction of this catalogue and other catalogues, as a result of the observations of the meridian circle at that time, were selected from the Catalogue contained in Volume XIV of the Publications of the Astronomische Gesellschaft. Much time was given to observations of these primary stars. In addition several general catalogues were formed for different purposes. The published results of Rogers' work, which occupy seven volumes of the Annals,[5] contain elaborate discussions of all the methods employed in observation and reduction, of determinations of proper motions, sources of errors, and comparisons with other catalogues.

In 1887, Pickering arranged to observe a southern zone in the plan of the Astronomische Gesellschaft for the revision of the Southern Durchmusterung. This work was intrusted to Arthur Searle, who spent the greater part of his time for about 20 years, with a staff of assistants, in making the necessary observations, in superintending their reduction, and in dis-

[5] H. A., **10**, 1871, 1872; **12**, 1874, 1875; **15**, 1886, 1892; **16**, 1886; **25**, 1893; **35**, 1894; **36**, 1896.

cussing the results. The observations of this zone, from $-9° 50'$ to $-14° 10'$, were begun in 1888, and were practically completed in 1898, although their publication was not concluded until 1914. The chief assistant in the observations was Mr. J. A. Dunne, and in the work of reduction, Mrs. Eddy and Misses Harwood, Hodgdon, Michaelis, Searle, and L. Winlock. The eight-inch meridian circle, used by Rogers for the observations of the northern zone, was employed by Searle with few modifications. When observations were begun with the instrument in 1870 a system of spider lines was employed, but was replaced in the following year by a glass plate with etched lines; this type of glass plate was used until 1900.[6]

The catalogue of the stars of the southern zone contains refined positions for 8337 stars. It is preceded by an elaborate description of the methods of observation and reduction.[7] The details of the observations are given in other volumes.[8]

In the final volume relating to this southern zone, Searle made a comparison of his results with other catalogues, using all accessible lists which contained any considerable number of stars in the region of the zone; 29 such catalogues were compared. The positions were all reduced to the epoch 1900.0. It was thought advisable to investigate the systematic differences which were likely to exist in the different catalogues and to apply such methods of adjustment as seemed to be demanded.[9]

Searle also made a discussion of the use of geometric methods in the theory of combining observations, referring to the methods generally used and the possibility of improving them.[10]

In comparatively recent times, photographic methods for the determination of position have, to a large extent, taken the place of the filar micrometer and meridian circle, except

[6] H. A., **41**, No. 7, 1902; cf. also H. A., **33**, No. 11, 1900.

[7] H. A., **67**, 1912.

[8] H. A., **62**, **65**, **66**, 1910–1911.

[9] H. A., **77**, 1914.

[10] H. A., **60**, No. 1, 1908.

in the case of fundamental stars. Especially is this true where only approximate positions are needed. For the extended lists of new variable stars, nebulae, and the like, published at Harvard, it has been necessary to give positions only with sufficient precision to insure the identification of the objects. When positions are taken from a catalogue, the simplest procedure is to bring forward the catalogue position to the desired epoch, but if this is not done, approximate positions can be rapidly determined from photographs with a reticle and reading microscope, by measuring the distances from two or more adjacent stars whose positions are known. Precise positions also can be obtained from photographs, and this has been done in some cases. Rectangular coordinates are often given in place of declinations and right ascensions.[11]

The Almucantar.—Some reference should be made to the almucantar, an ingenious invention of Chandler. The accuracy of his determinations of the right ascensions and declinations of stars in 1884 and 1885 rivalled those of meridian circles. In the almucantar, which floats on mercury, gravitational action about an imaginary vertical axis is substituted for motion of rotation about the horizontal axis of a meridian circle. In Chandler's final instrument a 4-inch telescope was used. This telescope was first pointed to the east of the meridian and the time of transit of a star was noted. Later, the time of transit of the same star was observed to the west of the meridian. Such observations served for the determination of time and latitude as well as right ascension and declination. Chandler demonstrated experimentally that the probable error of equilibrium must lie within one tenth of a second of arc, a quantity at the extreme limit of perception, or of indication by the spirit level.[12]

The accuracy of the almucantar observations is well shown in Chandler's latitude determinations. In observations made

[11] H. A., **48**, No. 1, 1903; **53**, Nos. 1, 2, 1905; **60**, No. 3, 1908.
[12] H. A., **17**, 1887.

in 1884 and 1885, he pointed out that a curious progression occurred throughout the series.[13] No explanation for this change was proposed at that time. In 1891, however, he published an article in which he showed that his observations could be interpreted only by a variation in latitude.[14] Meanwhile, Küstner had announced, in 1888, the variation of latitude as proved by German observations. Chandler's later masterly discussion of this subject does not properly belong to the history of the Harvard Observatory.

The principle of flotation had been recognized as early as 1825, but appears to have been forgotten until Chandler began his experiments in 1879. Since the latter date various floating instruments or almucantars have been constructed.[15]

[13] A. N., **112**, 113, 1885.
[14] A. J., **11**, 59, 1891.
[15] A. J., **21**, 57, 1900; M. N. R. A. S., **60**, 572, 1900; **61**, 315, 1901.

CHAPTER X

ASTRONOMICAL PHOTOGRAPHY

DAGUERRE announced the success of his experiments in photography in 1839, only a few months before the old Harvard Observatory was established at the Dana House. The early plates, called "daguerreotypes" after their inventor, were formed by sensitizing the polished surface of a silver, or silvered copper plate, and gave excellent portraits of individuals. Very long exposures were required, and landscapes, photographed today in a small fraction of a second, required exposures of six or eight hours.

Beginnings of Astronomical Photography.—The invention of photography opened the way to astonishing developments in astronomy, but not at once. Just as the triumph of Daguerre was the final outcome of nearly half a century of experimentation by many investigators, so the development of photography proceeded for nearly half a century more before it became a powerful factor in the advance of modern astronomy.

The three main stages in the progress of photography were the daguerreotype, the collodion wet plate, and the dry plate. Bright objects, such as the sun and moon, could be photographed with the daguerreotype, and later with wet plates. The astronomical world was obliged to wait, however, for the slow perfection of the dry plate before photography could be used extensively in stellar researches.

No sooner had the success of the daguerreotype been announced in 1839 than Arago suggested its useful application to astronomical research, confining the suggestion to the sun and moon on account of the lack of sensitiveness of the early

plates. It was in America, however, that Dr. John W. Draper in the following year (1840) obtained the first photograph of the moon, with an exposure of 20 minutes. Daguerreotypes were also used as early as 1842 at total eclipses of the sun, and the sun itself was photographed in 1845.

From 1849 to 1851, a series of photographs of the moon was made at the Harvard Observatory, arousing considerable enthusiasm among astronomers. The photographs were made with the 15-inch refractor, whose lens was corrected only for visual rays. The resulting pictures of the moon, although not in perfect focus, were the best obtained up to that time, though they could not rival the best visual drawings of the lunar surface. Indeed, despite all the marvellous photographs obtained by the giant telescopes of the present day, the rivalry between visual and photographic observations still persists in regard to the surface markings of the members of the solar system, especially of the planets. It is still claimed that fainter and more delicate details can be seen than photographed.

Progress of Stellar Photography.—It is in stellar astronomy, however, that photography has made its most important advances and distanced competition by visual methods—it is in stellar astronomy that the Harvard Observatory has made its most notable contributions. The first photograph of a star ever obtained was made at the Harvard Observatory in 1850 by Whipple, under the direction of W. C. Bond, using a daguerreotype plate with the 15-inch telescope. An image was obtained of α Lyrae, magnitude 0.14, and also of α Geminorum, a double star, magnitude 1.58, whose two components were indicated by the elongation of the image. No impression could be obtained of the Pole Star, or of any other star fainter than the second magnitude, however long the exposure. Instrumental and photographic difficulties prevented further experiments at that time.

The investigations were renewed under the direction of G. P. Bond in 1857 by Whipple and Black professional photographers

ɔ gave invaluable volunteer assistance. A better control :k had been provided for the 15-inch telescope, and the ·oduction of the collodion process in photography provided tes that were more sensitive and more easily manipulated. April, 1857, images were obtained of Mizar and Alcor on a gle plate with an exposure of 80 seconds, and images of the ghter component could be obtained in from 3 to 5 seconds. A es of plates of these double stars was made, and a study the positions and distances of the companion stars was ried out by G. P. Bond. The results were in close accord h the visual observations of Struve. Thus it was early wn that in double star observations photographic methods ld be expected to yield results rivalling in accuracy the best ıal observations.

n 1850, the limit of photographic attainment had been stars ghter than the second magnitude; by 1857, the limit had been ended to the sixth magnitude.[1] In 1858 G. P. Bond e the details of further photographic observations of double ·s, concluding with the following sentence:

> ıdeed in every direction the art seems to be susceptible of greater ection, which may yet render possible its extension, to stars four or magnitudes beyond our present limit (i.e. to the tenth or eleventh nitudes).[2]

n 1859 Bond demonstrated that a certain time, dependent the brightness of the star and on other conditions, elapsed :r the beginning of the exposure before any observable ge was formed. He suggested that, instead of the vague mates of magnitude then made visually (stellar photometry unknown at that date), precise determinations of magnitude e possible by a study of the size and intensity of the photophic images.[3] The three papers on this subject by G. P. ıd have been called the classics of astronomical photography. also wrote an enthusiastic letter on the subject to William

\. N., 47, 1, 1857.
\. N., 48, 1, 1858.
\. N., 49, 81, 1859.

Mitchell of Nantucket, in 1857, from which the following brief quotation is made:

> Suppose we are able finally to obtain pictures of seventh magnitude stars. It is reasonable to suppose that on some lofty mountain and in a purer atmosphere, we might with the same telescope include the eighth magnitude. To increase the size of the telescope three-fold in aperture is a practical thing, if money can be found. This would increase the brightness of the star images, say eight-fold, and we should be able then to photograph all the stars to the tenth and eleventh magnitudes, inclusive . . . What more admirable method can be imagined for the study of the orbits of the fixed stars and for resolving the problem of their annual parallax than this would be, if we could obtain the impressions of the telescopic stars to the tenth magnitude!

Henry Draper and the Beginnings of Stellar Spectroscopy.—To trace the development of astronomical photography in the world at large would involve a long account of the researches of many distinguished men—a subject beyond the scope of this work. Some reference must be made, however, to Henry Draper, for his work became intimately associated with the Harvard Observatory. Dr. Draper followed the scientific lines begun by his father, Dr. John W. Draper, who took the first lunar photograph. In 1881, Henry Draper obtained a photograph of the Orion Nebula on which stars were shown to the fourteenth magnitude. After about 20 years of experimental work carried on by many investigators, fairly reliable dry plates had become available about 1875. The nebular photograph taken by Draper was perhaps the first ever made which showed the images of stars as faint as could be seen with a telescope of equal aperture—a result rendered possible by improvements in the instrument, in the technique, and in the photographic plates. The photograph, by means of its power of accumulating the energy falling upon it, had thus become an instrument of research as powerful as the eye itself.[4]

As early as 1863, Huggins had attempted to photograph the spectrum of Sirius, but no lines were shown. The first

[4] Proc. Amer. Acad., **20**, 407, 1885; Washington Obs., 226, 1878.

photograph of a stellar spectrum in which the characteristic lines were visible was obtained by Henry Draper when in 1872 he took a spectrum of Vega in which four lines were seen.[5] Work of this nature was carried on for some years with slit spectroscopes by Huggins and Draper but was confined to bright stars.[6]

Astronomical Photography under Pickering.—Photographic investigations were again undertaken at the Harvard Observatory in 1882, under the direction of E. C. Pickering, assisted by W. H. Pickering, at that time an instructor in photography at the Massachusetts Institute of Technology. Instead of the 15-inch lens which was uncorrected for the actinic rays, portrait lenses were employed, at first one of 7 inches diameter and 37 inches focal length. A long series of experiments was carried out with this and other lenses, attached to an equatorial mounting, or at rest. As a result of these experiments, a new series of stellar photographs was begun in March, 1885, with a better instrument—a Voigtländer lens of 8 inches diameter and 45 inches focal length, corrected and mounted by Alvan Clark and Sons. The cost of this equipment was borne by the Bache Fund, and the telescope was called the "Bache Telescope." So successful did it prove to be in various ways that it was kept in almost continuous use, either at Cambridge or Arequipa, until 1923, when 53,754 photographs of the sky had been made with it.

With the Bache telescope the spectrum investigations of the Henry Draper Memorial were begun. By placing a large prism over the object glass, stellar spectra of excellent quality were obtained. The work of this instrument was later supplemented by that of various photographic telescopes of greater size, notably the 11-inch Draper and the 13-inch Boyden refractors. From one to four objective prisms were used, depending upon the brightness of the star. The length of

[5] Amer. Journ. Sci., **18**, 419, 1879.

[6] Phil. Trans. Roy. Soc., p. 669, 1880; Proc. Amer. Acad., **19**, 231, 1884.

the spectra thus obtained varied from 1 centimeter, or even less, to 10 centimeters. Even in the spectra of the smallest scale, the excellence of the definition permitted the classification needed for the various lists and catalogues of the Henry Draper Memorial.[7]

Construction and Guiding of Astronomical Cameras.— Various investigations into the general principles of photographic processes, in their application to astronomy, have been made by members of the Observatory. There is no essential difference between the lenses used for portraiture and those for astronomical work. Indeed, in the early days of photography, very large lenses were employed by professional photographers to avoid excessively long sittings, because the plates then obtainable were extremely slow. Such lenses were used by the Pickerings in their early investigations with only such regrinding as was necessary to produce the desired scale and to give good definition over a large field; some of the lenses needed no change. Barnard and others also used similar equipment with marked success.

The lenses first used were doublets, later employed in a much enlarged form in the 24-inch Bruce telescope. For many purposes a single achromatic combination corrected for the photographic rays has been used, a form similar to the ordinary visual telescope except in the corrections given to the lens. Such was the instrument made by the Henry Brothers of Paris, and employed in the formation of the Astrographic Catalogues and Maps.

Good lenses became generally procurable, but there were other problems. To obtain well defined photographs of a moving object, such as the moon or a star, the telescope must be carried forward by a suitable driving clock, or other apparatus, which will follow the object in its motion: the chief requirement is an arrangement by which the effect of the earth's rotation is neutralized. The apparent motions of the sun, moon, and

[7] Mem. Amer. Acad., 11, 179, 1888.

stars all differ, and must all be provided for, unless extremely short exposures are to be given.

The vast majority of the celestial photographs in the Harvard collection have been obtained with instruments guided by mechanical means, in many cases devised or improved by Professor W. P. Gerrish. An adjustable control clock regulates the motion of the telescope, so that it follows the apparent motion of the stars with such precision that the resulting images on a chart plate are nearly circular. With small and rigid instruments, the control clock is all that is usually necessary. For larger telescopes, however, the experiment becomes correspondingly more difficult. Further mechanical devices may be employed to advantage; but for instruments of great size, personal guiding of the telescope becomes necessary in order to obtain the best results. The image of a star, either in the field of the telescope itself or of the "finder," is followed visually and all irregularities of motion are promptly corrected by the observer. W. H. Pickering made an early investigation into some of the principles involved in celestial photography, as an introduction to his study of the Orion Nebula.[8]

The Photographic Image.—An investigation of the forms of images in stellar photography was begun by E. S. King in 1896. The form of an image is chiefly influenced by the rate of the clock, refraction, the adjustment of the polar axis, flexure, and any imperfection in form of the driving gears which would introduce periodic irregularities in the motion of the instrument. King showed that the usual supposition that a star moves on sidereal time is incorrect. Even on the meridian there is a deviation due to refraction. The instrument, too, may be adjusted on the true pole with its axis parallel to the axis of the earth, but, if it is adjusted by polar stars, its adjustment is on the refracted pole. The real motion of the star is never sidereal and rarely uniform. King made a careful determination of the corrections to clock rates which would allow for the

[8] H. A., 32, Part 1, 1895.

various irregularities caused by differential refraction, polar adjustment, flexure, and the like, and his results have been used in practice with much success.[9] A long, elaborate, and important series of investigations, dealing with many of the principles involved in photography, has also been carried on for many years by King. The results obtained are referred to later under the special problems concerned.[10]

Photography has entered into all departments of observational astronomy, and in some of them, as in spectroscopy, it has practically displaced visual observations. The great advances of the last half century would have been impossible without it. Most of the recent work of the Harvard Observatory has been based on celestial photographs. The great collection now housed at Cambridge contains some 300,000 photographs, which constitute a history of the sky for nearly half a century. Even the early plates do not appear to have suffered serious deterioration by lapse of time, and in many respects they increase in value with age.

The dream of G. P. Bond of a time when photographs of stars to the tenth magnitude might be obtained came true long ago, not many years after his early death. Had he lived to old age, he himself would have seen its fulfillment. Today stars to the tenth magnitude can be photographed in a fraction of a second, and with long exposures, stars many thousands of times fainter, below the twentieth magnitude. One may well wonder what the future will reveal.

[9] H. A., **41**, No. 6, 1902.
[10] H. A., **59**, 1912.

CHAPTER XI

STELLAR PHOTOMETRY, VISUAL AND PHOTOGRAPHIC

THE determination of the brightness of celestial objects by photometric methods has occupied a prominent place in the history of the Harvard Observatory. In preceding chapters much has been said of researches concerning the brightness of various members of the solar system, and what follows relates chiefly to the photometry of the stars.

The Beginnings of Photometry.—The desirability of grouping the stars according to their brightness, or magnitude, was recognized by ancient astronomers. The earliest record of an attempt of this nature, which has come down to us, is given in the Almagest of Ptolemy (Epoch, 138 A.D.). The results there given, however, appear to have been derived from the observations of Hipparchus (second century B.C.). All the stars visible to the eye are divided in the Almagest into six classes, called "magnitudes," the first group including 20 of the brightest stars, the sixth group or magnitude including stars faintly visible, and the other groups, the intermediate magnitudes. Ptolemy also used the terms "greater" and "less" to indicate magnitudes brighter or fainter than the average magnitude of a class, thus permitting more precise estimates of the individual stars. The letters representing these words have been replaced in modern times by decimals, at first expressed to tenths, and later, with the perfection of photometric methods, to hundredths, and even in some cases to thousandths of a magnitude.

For many centuries the world accepted the astronomy of Ptolemy with little or no attempt to question its accuracy. In the tenth century, however, Sûfi made a valuable revision of

the magnitudes in the Almagest, giving additional stars. In the catalogue of Ulugh Beg (Epoch, 1437), the magnitudes of Sûfi are retained. The work of estimating the visual magnitudes of the stars was enormously extended in more recent times by many observers, especially by Tycho Brahe, the Herschels, Struve, Argelander in his Uranometria Nova and with Schönfeld in the Bonn Durchmusterung, Houzeau, Heis, and Gould and his associates in the Uranometria Argentina and in the Cordoba Durchmusterung.

Peirce's Early Photometric Experiments.—Photometric determinations of magnitude—that is measures with a photometer used visually—made little advance until the closing quarter of the nineteenth century. In 1871, when Charles S. Peirce at the Harvard Observatory planned a series of photometric observations of certain stars, the only photometric observations known to him were those of Seidel, of Munich, who had observed in all 208 stars during the years 1844 to 1860, using a Steinheil photometer; and a few observations by Rosen at Poulkova and by Zöllner. Wolff's observations of 475 stars made at Bonn from 1869 to 1875 with a Zöllner photometer were not published until 1877.[1]

In attempting to reform the existing scales of magnitudes by the aid of instrumental photometry, Peirce decided that they should be so adjusted that equal numerical differences in magnitude would be represented by equal ratios in light. Fortunately, by Fechner's psychophysical law, the ratio of light between successive magnitudes already in use was approximately constant, although the results obtained by different observers varied considerably even among the naked eye stars. Peirce attempted to reduce all the discordant scales of magnitudes of the various observers to one, and to render his magnitudes accordant with it. He made no reference to the scale proposed by Pogson, and later adopted by Pickering, in which the magnitudes were obtained by the use of 0.400

[1] H. A., 9, Chap. 4, 1878; 14, 329, 1884.

as a divisor of the logarithmic ratios. Previously, values as low as 0.350 and as high as 0.440 had been involved.

It is obvious that the work of Peirce during the years 1871 to 1875 was of a pioneer nature. It was begun at the Observatory in Cambridge under the general direction of Joseph Winlock, at that time director, and was carried forward in Washington and elsewhere. The observations were made with a Zöllner astrophotometer attached to a small portable telescope. In this form of photometer, an artificial star, produced by lamplight shining through a small hole, is brought into the field of the telescope. Its light is then reduced by means of a Nicol prism to equal that of the star to be compared. A cap was placed over the lens to reduce the brightness of the stars when necessary. With such an apparatus Peirce measured the light of 494 stars, in declination from 40° to 50°, North. His plan was to obtain the magnitudes of all the stars in Argelander's Uranometria, between the above limits, in order to furnish the magnitudes of stars which might be observed "at every altitude, with which to compare others in forming a new uranography."

The value of Peirce's work was much increased by his discussion of the nature of light and the colors of many stars, and by his elaborate comparison of the magnitudes of stars given in the lists of Ptolemy, Sûfi, Ulugh Beg, Tycho Brahe, the Herschels, Seidel, and the Bonn Durchmusterung.[2]

The Polarizing Photometer and the 15-inch Telescope.— At the beginning of 1877, when Edward C. Pickering began his duties as Director of the Observatory, the need for further systematic and extended photometry of the stars was urgent. The work already done, while valuable in throwing light on the nature of the problem, was distinctly preparatory, and gave little material for the use of astronomers. It is true that *estimates* of magnitudes had been made for several hundred thousand stars in the various Durchmusterungen and elsewhere, but they were on no uniform scale.

[2] H. A., 9, 1878.

For the naked eye stars, the estimated magnitudes were fairly accordant, but the introduction of telescopes of greater power brought fainter stars into the problem. Large discordances occurred in the estimates of the fainter Durchmusterung stars, and for very faint stars the estimates by different observers sometimes differed by several magnitudes, chiefly because of the diversity of the scales employed.

As a physicist already interested in photometry, Pickering at once became absorbed in this problem. In spite of the few brief lists of stars which had been observed photometrically, the subject needed to be approached independently and placed on a permanent foundation. It was desirable that the magnitudes of the lucid stars, well established by many centuries of usage, should remain unchanged except for minor corrections, and it was hoped that the system might be capable of indefinite extension by the adoption of a uniform scale of magnitudes which would command the approval of the astronomical world. Uniformity was achieved by the adoption of the scale proposed by Pogson, that the ratio of one magnitude to the next should be fixed as the fifth root of 100, 2.512, or more exactly, as the number whose logarithm is 0.4.[3] This ratio gives results in essential harmony with the estimates of magnitudes of the brighter stars since the time of Ptolemy. It is a natural outgrowth of the conclusion of Sir John Herschel, about 1830, that a star of the first magnitude is one hundred times brighter than one of the sixth magnitude. It was necessary, also, to fix upon a zero point for the scale, and this was done by bringing the magnitudes into general agreement with the values given in the Uranometria Nova and the Bonn Durchmusterung. These principles for the determination of stellar magnitudes both for zero point and scale have been generally accepted by astronomers of all countries.

Pickering's first photometric observations were made with the large refractor, to which were attached various photometers devised by himself. Most of these were polarizing photometers.

[3] M. N. R. A. S., **17**, 13, 1856; Radcliffe Obs., **15**, 296, 1856.

Wedge photometers were also occasionally used, but Pickering early decided that whenever possible it was better to avoid the use of any instrument in which the images of the stars are compared with that of an artificial star.

The photometer commonly used with the large refractor had movable double-image prisms and a revolving Nicol attached to a graduated circle. When two adjacent objects were viewed in this instrument, two images of each were formed by the double-image prism, either of which, by turning the Nicol, could be made as faint as was desirable. Whatever their relative light, the faint image of the brighter could be reduced to equality with the bright image of the fainter object. The true relative magnitudes of the two objects could then be deduced from the angle through which the Nicol was turned. With a photometer of this kind only adjacent objects can be compared, such as the components of double stars, or the satellites of planets. During the years 1877 to 1879, observations of many double stars were made by Pickering, assisted by Searle and Upton. In many cases the difference in light between the components of double stars was more than 10 magnitudes, and in a few cases, from 12 to 13 magnitudes. Such objects are extremely difficult of precise observation with any photometer, and the results are doubtless affected by considerable errors. In publishing this work no magnitudes of the stars were given, but only the differences in magnitude between the components, using the Pogson scale; no zero for the scale of magnitudes had at that time been adopted.[4]

The Harvard Photometry and Its Extensions.—Soon after he assumed the duties of director, Pickering began to plan the extensive stellar photometric surveys which in later years contributed so much to the advancement of astronomy. Much experimentation was necessary before an instrument suitable for rapid and precise measurements was ready. The

[4] H. A., 11, Part 1, 1879.

photometer, devised by Pickering and constructed by the Clarks, was called a "Meridian Photometer." With a meridian instrument, the stars may be observed in the most favorable position and can be brought into the field of view and identified with ease and rapidity. The observer remains at all times in the same position as regards the eyepiece, the line of sight is horizontal, and comparisons are made with other stars, not with artificial standards.

The first meridian photometer was ready for use early in 1879. The lenses had a diameter of 1.6 inches and a focal length of 32 inches. It was designed especially to obtain the relative magnitudes of all stars, of the sixth magnitude and brighter, readily visible at Cambridge. It consisted essentially of a horizontal telescope pointing east or west, having two similar objectives and a single eyepiece. A right angled prism was placed in front of each lens. One of these was adjusted so as to bring into view the Pole Star, α Ursae Minoris, which could be kept in any desired position by small readjustments in the position of the prism. The other prism could be turned about the axis of the instrument so as to bring into view a star of any declination when near its meridian passage. The collimation could be altered somewhat to permit an extension of the time of observation. The two pencils of light, one from the Pole Star and the other from the star to be compared, passed through a double-image prism, compensated by glass, which gave two pencils for each star. By varying the angle of the prism and the glass, the ordinary image of one star was made to coincide with the extraordinary image of the other star, when by the revolution of a Nicol the images could be equalized. Readings of an attached graduated circle were made, from which the relative magnitudes of the two stars could be derived.

With this instrument, from 1879 to 1882, 4260 stars north of declination $-30°$ and of magnitude 6.2 and brighter were observed by Pickering, assisted by Searle and Wendell. In this early work all the stars were compared directly with the Pole

Star which was assumed to have the magnitude 2.0. The magnitudes of the stars thus obtained were subject to three corrections. The first was due to any difference in the images formed by the two objectives and was derived from comparisons of the Pole Star with itself, at the beginning, middle, and end of each series. The second correction was for atmospheric absorption. For the best determination of this correction many observations and elaborate discussions were made. The third correction was due to any error in the assumption that the magnitude of the Pole Star is 2.0. This correction, being constant, serves merely to fix the zero of the scale of magnitudes. Since it seemed desirable to have the magnitudes accord in general with the estimated magnitudes of Argelander, a correction of +0.27 magnitude was obtained by a comparison of the corresponding magnitudes of 100 circumpolar stars of about the fifth magnitude, which were common to the Bonn Durchmusterung and Uranometria Nova, and to the Harvard Photometry. These stars, whose magnitudes were determined with special care, were taken as standards, and in all later photometric work the final magnitudes were made to depend on the mean magnitude of the circumpolar stars, so that any variation in the light of the Pole Star, which was still used as an intermediary, would have no effect on the results. Any other star of suitable magnitude would be satisfactory, and λ Ursae Minoris and σ Octantis have been so used. The correction first used, +0.27, combined with the correction for absorption, gave 2.15 as the magnitude of the Pole Star. A later mean value derived from many observations is 2.12.

At the beginning of the photometric work, careful observations of various kinds were made to determine whether the light of the Pole Star was constant, with the conclusion that its light did not vary sensibly. Nevertheless, in 1911, Hertzsprung showed that it was a variable star of short period. W. W. Campbell had previously discovered that it was a spectroscopic binary. The range of variation, as determined by different observers, is between 0.08 and 0.17 magnitude.

This variation was probably too small for detection by the methods in use in 1879.[5]

During the years 1882 to 1886, wedge photometers were used with the 15-inch telescope by Searle for the observation of faint stars. The polarizing photometers were not suited to this work. One of the wedges employed was made by Hilger of London, under the supervision of Professor Pritchard, who undertook to superintend the construction of a wedge photometer as nearly as possible like the instruments in use at the University Observatory of Oxford. The Harvard observations were undertaken not only to extend the knowledge of the relative brightness of faint stars, but especially to determine the relations of the scales of magnitude used by different observers. In the photometers employed, a wedge of tinted glass, optically compensated by cementing to it a similar wedge of clear glass in a reverse position, is placed in the focal plane of the telescope. This completed wedge carries an opaque bar or heavy line parallel to the edge of the wedge. The interval between the transit of a star across the bar and its disappearance in the wedge is the observed quantity from which the brightness of the star is deduced. Various difficulties and uncertainties, which are thoroughly discussed, arise in the use of such a wedge. The zero and scale were based on the photometric results of the meridian photometers, which were already in use before the completion of this work. The first observations undertaken were of the faint stars in the Bond Zone from $+0°50'$ to $+1°00'$. The results were considered so satisfactory that the work was extended to two narrow zones from $+49°50'$ to $+50°00'$, and from $+54°50'$ to $+55°00'$. The object of the latter observations was to furnish aid in the determination of the relation of the Durchmusterung magnitudes of the fainter stars to the Harvard photometric scale.[6]

The catalogue of 4260 stars north of $-30°$ (measured with the first meridian photometer) which became known as the

[5] H. A., **14**, Part 1, 1884; H. C. 174, 1912.

[6] H. A., **13**, Part 2, 1888.

"Harvard Photometry," was only the beginning of the photometric surveys which Pickering had planned. These surveys were designed to include much fainter stars, and to extend over the whole sky. For this purpose a larger instrument was necessary, and a new one was constructed on the same general principles as the small meridian photometer. The chief modification was in the use of mirrors instead of right angled prisms to reflect the light of the stars into the objectives. The lenses of the new instrument were four inches in diameter and about five feet in focal length.

With this photometer stars to the ninth magnitude could be observed readily, and even to the tenth magnitude under especially favorable circumstances. As in the former work, four comparisons or settings were made on each night, and the observations were carried on for three or more nights. The principal work at first undertaken with this instrument, and carried out during the years 1882 to 1888, was the determination of the magnitudes of a sufficient number of stars in the Bonn Durchmusterung to serve as standards for a photometric revision of that work. All the stars not called fainter than 9.0 in the Durchmusterung, in zones 20′ in width, at intervals of 5°, were observed. The plan was extended to declination −20°, to include the observations of Schönfeld. The observations were made by Pickering and Wendell; 20,982 separate objects were observed in 1067 series. They included a few variable stars, planets, and satellites.[7]

A complete discussion of this work was made by Pickering, who gave also a description of the instrument, an account of the stars selected, the circumpolar standards, atmospheric absorption, and the methods employed, as well as a comparison of the results with other modern catalogues, and a reduction of the Bonn Durchmusterung to the photometric scale. The Harvard and Bonn scales coincide at the fourth and eighth magnitudes.[8]

[7] H. A., **24**, 1890.

[8] H. A., **23**, 1890, 1899.

Many later investigations were undertaken with the 4-inch meridian photometer. Perhaps the most important of these was the extension of the Harvard Photometry to the far southern stars, thus making it cover the whole sky. The methods employed were similar to those already described; σ Octantis, whose magnitude is 5.47, was used as the comparison star in all the observations, but the final magnitudes of the measured stars were independent of the brightness of the Pole Star. They were derived from the mean magnitude of standard stars selected from the catalogue of the northern Harvard Photometry. A number of these stars of known magnitudes were measured in each series. The zero and scale, therefore, should be the same as that of the northern catalogue. Nearly 8000 stars were observed during the years 1889 to 1891. The observations were all made by Solon I. Bailey. Preliminary reductions of the series were carried out in Peru and Chile as soon as possible after the observations were made, but the final reductions and the publication of the results were carried out in Cambridge under the direction of Professor Pickering.

Before the establishment of the Boyden Station at Arequipa, while various sites were being investigated, the photometer was in use. Thus at different times observations were made at "Mount Harvard," Peru (near Chosica), latitude south about 12°, altitude 6500 feet; at Arequipa, Peru, south 16°22′, 8000 feet; and at Pampa Central, Chile, south 23° 10′, 4530 feet.[9]

During the years 1891 to 1894, Pickering, using the 4-inch meridian photometer, made a revision of the northern Harvard Photometry. The original observations had been made 10 years earlier with a smaller instrument, and a redetermination of the magnitudes was desirable. Several hundred additional stars were also observed.[10] The history and description of the photometer, the methods of observation and reduction, and other matters relating to the work of this instrument during the years 1891 to 1898, were published later.[11]

[9] H. A., **34**, 1895.

[10] H. A., **44**, Part 1, 1899.

[11] H. A., **44**, Part 2, 1902.

From 1895 to 1898, Pickering used the 4-inch photometer in forming a photometric Durchmusterung[12] of all stars of magnitude 7.5 and brighter, north of declination $-40°$. This investigation was extended to the south pole during the years 1899 to 1900, by Bailey at Arequipa,[13] for all stars of magnitude 7.0, and brighter. During the formation of the northern Durchmusterung, photometric observations of a large number of variable stars and other miscellaneous objects were made by Pickering.[14]

By the year 1906, more than a million comparisons of nearly fifty thousand stars had been made with the 2-inch and the 4-inch photometers.[14a] Some of the brighter stars had been measured many times, and, because the resulting magnitudes inevitably varied somewhat, some confusion prevailed as to which determination should receive the preference. Pickering, therefore, prepared a revision of the magnitudes of all the brighter stars, by taking the mean values of all the determinations given in the different Harvard catalogues. Equal weights were given to each catalogue, independently of the number of observations concerned. The mean magnitudes thus derived from all the measures made during the years 1879 to 1906, for stars of magnitude 6.5 and brighter, were published in Harvard Annals, **50**, 1908. This catalogue received the name of the "Revised Harvard Photometry," and became the standard reference work for the magnitudes of the brighter stars. An extension of the same work to the fainter stars, measured in general with the 4-inch photometer, was published in Harvard Annals, **54**, 1908, and gave the revised magnitudes of 36,682 stars fainter than magnitude 6.5. Volumes **50** and **54** of the Harvard Annals really constitute a single work, giving the best visual magnitudes at that time available. In Harvard Annals, **50**, was also given the class of spectrum, taken in general from Harvard Annals, **27** and **28**.

[12] H. A., **45**, 1901.

[13] H. A., **46**, Part 1, 1903.

[14] H. A., **46**, Part 2, 1904.

[14a] H. A., **14**; **23**; **24**; **34**; **44**; **45**; **46**.

Stars but little fainter than the ninth magnitude could be observed with the 4-inch meridian photometer. The further extension of visual photometry demanded the observation of much fainter stars, and Pickering proceeded to the construction of a larger instrument, consisting of a 12-inch horizontal telescope into which the light of the stars was reflected from a rotating silvered glass mirror, inclined 45° to the axis of the instrument. Although the instrument remained a meridian photometer, the other principles involved in its construction were rejected, for the express purpose of avoiding loss of light in polarization. An artificial star was used for all the comparisons, and a wedge of shade glass to reduce the light, instead of a polarizing apparatus. With this instrument Pickering first extended his Durchmusterung revisions to fainter stars.[15] A great number of observations also were made of the fainter comparison stars for variables; of the Bond Zone from 0°40′ to 1°00′; of a sequence in the Pleiades; of sequences of the stars in the various Standard Regions, 30° square, into which he had divided the sky; and in the Kapteyn Selected Areas. Observations were also made of other special objects.[16] For many years Miss Florence Cushman took an important part in the work of reduction and preparation for publication of the photometric observations.

During many years important photometric observations were made by Wendell, using the 15-inch telescope with polarizing photometers devised by Pickering. Since with these photometers only adjacent stars could be compared, the sources of error due to differences in the condition of the sky at various points were avoided. The observations by Wendell were made with unusual care and skill, and the results are correspondingly precise. The investigations carried on by him consisted chiefly of observations of variable stars and of the fainter comparison stars for variables.[17]

[15] H. A., 70, 1909.
[16] H. A., 74, 1913.
[17] H. A., 69, Part 1, 1909; Part 2, 1913.

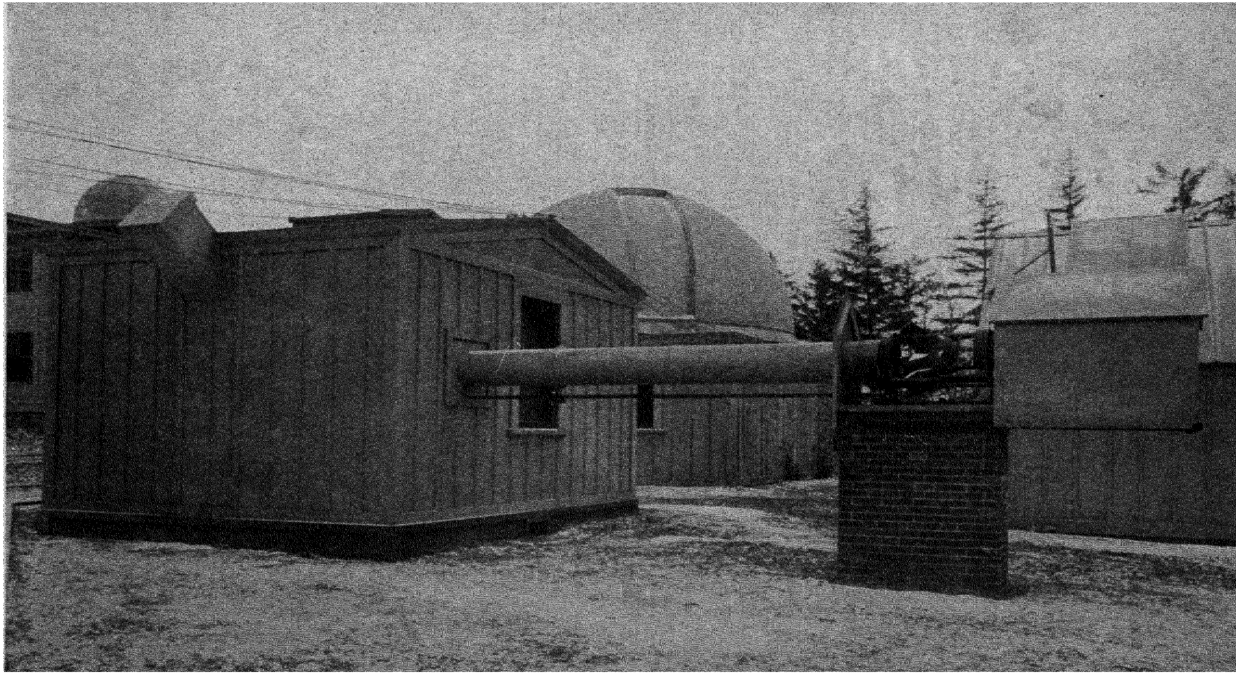

PLATE XIII.—THE 12-INCH MERIDIAN PHOTOMETER.

(Facing page 134)

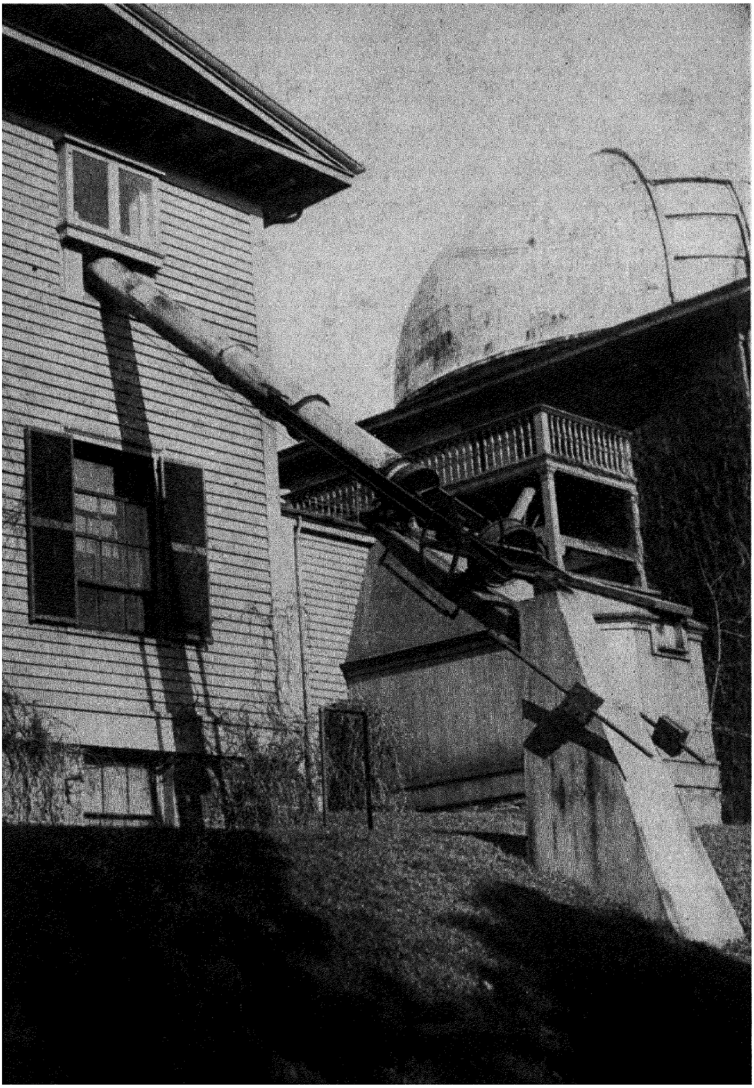

PLATE XIV.—THE 12-INCH POLAR TELESCOPE.

From 1885 to 1917, many minor photometric investigations were made in Cambridge, Arequipa, and South Africa.[18] Pickering planned for several years to extend the Harvard Photometry to still fainter stars by the use of the Common 60-inch reflector. Much time was spent in adapting the instrument to this work. The results were not satisfactory, however, since the images of the stars were poor. Meanwhile, the development and progress of photographic photometry, with its greater possibilities, made a further extension of visual photometry of small importance.

Photographic Photometry.—One of the most striking features in the development of modern astronomy is the part played by photography. Its possibilities were early recognized. As a result of pioneer experiments in stellar photography, begun at the Harvard Observatory by Whipple and Black in 1850, George P. Bond was able to state by 1857 that . . . the intensity and size of the images, taken in connection with the length of time during which the plate has been exposed, measure the relative magnitudes of the stars.[19] Little or no attention was given to this important line of research for many years following, chiefly owing to lack of funds.

Preliminary experiments in celestial photography, including photometry, were begun in 1882 by E. C. Pickering and W. H. Pickering. A photographic lens of 2½ inches aperture was used at first, and later one of eight inches. Among other results, it was found that accordant relative magnitudes could be obtained from stellar trails.[20]

In 1885, under the direction of E. C. Pickering, the subject was again taken up in a serious attempt to find the best methods for the determination of photographic stellar magnitudes. The instrument employed was an 8-inch Voigtländer photographic doublet, reground by the Clarks, of 44 inches focal

[18] H. A., **18**, Nos. 1, 2, 3; **33**, Nos. 1, 10; **64**; **72**, Nos. 4, 5, 6, 7; **76**, Nos. 9, 12; **80**, Nos. 7, 13.

[19] Letter of G. P. Bond to William Mitchell, July 6, 1857.

[20] Mem. Amer. Acad., **11**, 179, 1886.

length; so that the scale of the plates agreed with that of the Bonn Atlas. The measures and computations were made by Mrs. Fleming. It was pointed out that for such determinations the images of the stars may be either in the form of points, lines, or surfaces. When they are trails, a correction for declination is necessary. Points and trails were utilized in this work. Comparison scales were formed by successive images of a star, having exposures of 3^s, 9^s, 27^s, 81^s, 243^s, and 729^s. The ratio of three between exposures was found to give images differing by approximately one magnitude. Scales were also made by the use of different apertures. Photographic magnitudes were found for 1009 stars within one degree of the North Pole, 420 stars in the region of the Pleiades, and 1131 stars near the equator. The plates were all reduced to a common scale, which was compared with that of the Harvard Photometry. Various difficulties arose, partly owing to a want of photometric magnitudes of the faint stars. Comparisons were also made with the scales of Wolf and MM. Henry.[21]

Whatever of interest and value the above results may have had, they were in no sense final. For several years following, many experiments and measures of photographs were made, but, owing to the difficulties involved and the lack of any absolute photographic scale of magnitudes, little progress was made.

The determination of photographic magnitudes would be simple except for the great number of variations which occur in photographic processes. One method of measurement is by the use of a glass scale, containing a succession of stellar images of different intensities, made by one star with different exposures, or by a number of stars with the same exposure, or by the use of different apertures. Images of the stars whose magnitudes are desired, including a suitable number of standard stars of known magnitude, are then compared with the scale images. The observations thus obtained form a

[21] H. A., **18**, No. 7, 1890.

series from which the desired magnitudes can be derived. In reality, however, many complications and difficulties enter, and the reductions may become complex and the results doubtful. The methods and difficulties were carefully discussed by King, Miss Leavitt, and others in the various publications referred to in this chapter.

King's "Absolute" Measures of Photographic Magnitude.—Beginning about 1900, an important and independent contribution to the determination of photographic magnitudes on a uniform or absolute scale was made by Edward S. King. Preliminary investigations regarding the action of photographic plates had been undertaken as early as 1896. These dealt with the advantages and difficulties of photographic processes and the technique necessary in order to obtain reliable results.[22] The great power of photographic methods for the determination of stellar magnitudes is to some extent balanced by a multitude of difficulties which tend to introduce systematic as well as accidental errors. King's first photometric research was the determination of the photographic intensity of various sources of light. The scale was that of the Harvard Photometry. Apparatus suitable for the investigation was devised by King. The absorption of the lens of the 11-inch Draper telescope was determined, and the way was opened for the successful extension of photographic photometry.[23]

After the application of his methods to the photometry of the moon and planets, King undertook the determination of the photographic magnitudes of the bright stars by means of extra-focal images. Seven foci were used, and their relative photometric values were determined. The exposure was 60 seconds in all cases. Polaris and other standard stars were included in each series. To eliminate accidental errors, observations of each star were made on five or more nights. Magnitudes were obtained for 33 stars. In order to minimize

[22] H. A., 59, No. 1, 1912.
[23] *Ibid.*, No. 2.

the errors involved in photographic processes, as far as possible, the following rules were observed: that the light of all the stars should be equalized; that the exposures should all be of the same duration; that the stellar images to be compared should be on one plate and developed simultaneously; and that the measures should be repeated several times.[24] This investigation was extended later to include 76 stars, in general of magnitude 3.5 and brighter. In the catalogue of these stars, in which their photographic and photometric magnitudes occur, the class of spectrum, taken from Harvard Annals, **50,** is also given. The mean differences between the photometric and photographic magnitudes of 109 stars, in relation to their spectral classification, are given in a special table. The proof of this definite relation constituted an advance of great importance. The zero of the scale adopted made the photometric and photographic magnitudes equal for stars of Class A. It was shown that the differences between the magnitudes varied systematically from −0.40 for Class Oe5 to +1.68 for Class M. These results were slightly modified later by the data derived from a greater number of stars. They make it possible to obtain the photographic magnitudes of all stars whose photometric magnitude and spectral classification are known.[25] His investigation was later extended to include 153 stars.

In regard to his methods, King stated:

> . . . that the photographic magnitudes of the 153 stars here given are "absolute" magnitudes: that the scale, or the relation of star to star, is independent of any other series or system of magnitudes, visual or photographic. All the data for determining these relations have been derived from the plates used in this investigation. The only point of contact with the photometric magnitudes of H. A., **50** has been the condition, that the mean of the photographic magnitudes for stars of Class A should agree with the photometric values.

In connection with his magnitude work, King discussed the question of an absorbing medium in space, and deduced some

[24] *Ibid.*, No. 4.
[25] *Ibid.*, No. 5.

vidence of its existence.[26] The subject was again considered ιter when much more extensive material was available. King ɔncluded that:

All the indications point to the presence of an absorbing medium in ›ace, or some factor which produces effects similar to absorption, by aking the more distant stars redder.[27]

ı a still later consideration of the subject, King presented ıe hypothesis that a local cloud of absorbing matter, extending 'om the sun to at least 100 light years, envelops our local star uster.[28]

King's photometry was later extended to include the bright ;ars of the southern sky and to include results obtained by the se of different instruments.[29] He also, by means of photo- raphs made with the 24-inch reflector, carried out his measures › stars as faint as the eleventh magnitude.[30]

Although the out-of-focus methods of King gave excellent :sults, their extension to very faint stars would be difficult, not impossible. The adoption of an absolute scale and zero oint, by the international committee on magnitudes, provided secure and permanent foundation for future work. The scale 'as the same as that of the Harvard Visual Photometry, 'here the ratio is 2.512, or the quantity whose logarithm is .4. The zero finally adopted makes the photometric and hotographic magnitudes equal for stars of Class A, of magni- ıdes from 5.5 to 6.5.[31]

The North Polar Sequence.—When Pickering, in 1906, efinitely began on a large scale the determination of photo- raphic magnitudes, he had already been experimenting for bout 20 years on the subject, but had been delayed by the ıherent difficulties of the problem and the lack of an absolute

26 *Ibid.*, No. 6.
27 H. A., 76, No. 1, 1916.
28 H. C. 299, 1927.
29 H. A., 76, Nos. 5 and 6, 1915.
30 *Ibid.*, No. 10.
31 A. N., 186, 40, 1910.

scale. In 1907, he announced his plan for the formation of a standard Polar sequence, to be used in extending the uniform scale of photographic magnitudes to the whole sky. Work on such a plan had already been in preparation for several years. In this investigation Miss Henrietta S. Leavitt, by her unusual ability, originality, and enthusiasm, became the leading figure, and to her Pickering intrusted the execution of his plans. The precise determination of the Polar Sequence was of primary importance. Its value in the progress of photometry could hardly be overestimated, for as soon as this sequence should be definitely established and accepted by astronomers, its scale of magnitudes could be transferred by photographic methods to any region in the sky. This has now been done extensively.

The North Polar Sequence, as finally adopted, consisted of 46 stars between the fourth and twenty first magnitudes. An additional 29 stars were measured, as well as 21 faint stars, comprising all that could be measured within 3′ of the Pole on plates made with the 60-inch Mount Wilson reflector. This made in all 96 stars. In the adopted sequence, all stars brighter than magnitude 11.4 are of Class A, with the exception of one F star; 12 of the additional stars referred to above, from magnitude 6.8 to 13.5, form a sequence of red stars. One of the chief difficulties in the way of obtaining precise magnitudes on an absolute scale is that due to color, which leads to variations in magnitude depending on many factors, such as differences in the lenses and mirrors, in photographic plates, and in developers.

The magnitudes of the 96 stars were investigated on 299 photographs taken with 13 different telescopes, with apertures varying from 0.5 inch to 60 inches. For stars of such great range in magnitude, telescopes of different size were necessary; also, since the errors involved are often large, the variety of photographs employed was expected to cause the errors to balance one another more or less. Both refractors and reflectors were used. A number of independent methods were used in the hope of reducing systematic errors; for example, different foci for out-of-focus images; Iceland spar to reduce the light

by a computed amount; objective screens; varying apertures; and different exposures. All these methods are subject to large systematic errors, and different plates taken by the same method under apparently similar conditions often give diverse results, so that too much weight should not be assigned to the results of a single investigation. In all cases, corrections must be determined and applied as far as possible.

The color equation was found to vary for different instruments, as was to be expected. Miss Leavitt recommended the adoption of the following definition:

> Photographic magnitudes coincide with photometric magnitudes on the Harvard System for stars having spectra of Class Ao between the magnitudes 5.5 and 6.5, and are fainter than the photometric magnitudes by 1.00 magnitude for stars having spectra of Class Ko between the same limits.

The results given in the table of adopted magnitudes were compared with the photographic magnitudes obtained at the Göttingen, Yerkes, and Mount Wilson Observatories, by King at Harvard, and by others. Later researches have shown that some modifications in the magnitudes are necessary.[32]

The term "absolute" magnitude was frequently used by Miss Leavitt in her publications, and sometimes by other investigators of that period. As employed by them it simply meant the finally accepted magnitude of a star on an absolute scale, whether photometric or photographic. The absolute magnitude of a star in the usage of the present day is the apparent magnitude the star would have at a distance of ten parsecs.

The Standard Regions.—Recognizing the impossibility of determining physical constants for all faint stars, Pickering, as early as 1884, devised a plan for dividing the whole sky into 48 equal regions. These became known as the "Harvard Standard Regions." The plan, as developed later, involved a study of all the bright stars in the regions, but for the fainter

[32] H. A., 71, No. 3, 1914; H. C. 108, 1906; 125, 1907; 150, 1909; 160, 1910; 170, 1912.

stars, a single sequence for each region near the center. In 1905 the more extensive plan of Professor J. C. Kapteyn, having 206 "Selected Areas," seemed destined to supplant the Standard Regions, but as much work had already been done on them, Pickering decided to complete the original plan. A sequence was therefore selected near the center of each region, consisting in general of stars from the sixth or seventh to the sixteenth or seventeenth magnitude. For the stars of these sequences, the photometric magnitudes are given, derived from Pickering's visual observations (extending to about magnitude 13.0 for all stars as far south as declination $-15°$) and from observations by Bailey for regions farther south. Fainter stars were beyond the reach of the photometers in use. The photographic magnitudes were determined by Miss Leavitt; the classification of the spectra by Miss Cannon; and the positions by Miss Walker. For the determination of the photographic magnitudes, duplicate exposures were made at first on the same plate, one of the Polar Sequence, and the other of the sequence to be measured. Later, the plates were made in series. The sequences in the Standard Regions at declination $+15°$ were used to extend the same scale of photographic magnitudes to regions too far south to be compared directly with the Polar sequence.[33]

Standards of Magnitude for the Astrographic Catalogue. The International Committee on Photographic Magnitudes recommended to the various observatories which took part in the preparation of the Astrographic Map of the Sky that the magnitudes of the stars concerned should be reduced to the scale of the Polar sequence. It also recommended that a single observatory should make a comparison for selected parts of the sky.[34] An offer from the Harvard Observatory to carry out this suggestion was accepted, and the investigation was undertaken by Miss Leavitt. Sequences of from 15

[33] H. A., **71**, No. 4, 1917.

[34] Bul. du Com. Internat. Perm. Carte du Ciel, **6**, 391, 1913.

to 22 stars were selected near the centers of the overlapping zones, and the photographic magnitudes were determined by a comparison with the stars of the North Polar Sequence by the methods already described. The results for the northern zones were published first. They include 108 series, from declination $+4^\circ.5$ to $+64^\circ.5$.[35]

The prosecution of this work was interrupted by the death of Miss Leavitt in 1921, but later it was carried forward by Miss Walker, under the direction of Dr. Shapley. The additional sequences needed to complete the investigation for the southern sky from declination $-2^\circ.5$ to $-64^\circ.5$ were 96 in number.[36]

Kapteyn's Plan of Selected Areas.—A large and important contribution to the determination of photographic magnitudes was made in connection with Kapteyn's Plan of Selected Areas. For the execution of his scheme, Kapteyn was obliged to depend on the cooperation of other observatories. Pickering offered the resources of the Harvard Observatory to furnish certain data necessary to the progress of the plan. But first need was for charts of all the selected areas, 206 in number, distributed over the whole sky. This necessity was met by photographs of these areas. For the northern sky, plates were made with the Metcalf 16-inch telescope, having exposures of 60^m and 1^m, and showing stars to about the sixteenth magnitude. For the southern sky plates were made with the 24-inch Bruce telescope, having exposures of 120^m, and showing stars to about the seventeenth magnitude. Both instruments were photographic doublets.

The Harvard Observatory also furnished photographic magnitudes on the international scale of a sequence of stars at the center of each area, to be used as standards. This part of the work was carried out by Miss Leavitt. The methods employed were essentially the same as in the case of

[35] H. A., **85**, No. 1, 1919.

[36] H. A., **85**, No. 7, 1924; No. 8, 1926.

the Harvard Standard Regions referred to above. Twelve photographic plates were received from the makers in a sealed box. These plates were exposed successively in the telescope for exactly 10^m, the first, sixth, and twelfth on the North Polar Sequence, and the remaining plates on the desired areas. Harvard Standard Regions were also included. Southern areas were photographed with the Standard Regions at $+15°$. The magnitudes of all the sequence stars were derived at Cambridge and sent to Groningen. All other reductions as well as the labor of publication were done under the direction of Kapteyn. The photographic magnitudes in the Kapteyn catalogues were determined from the estimated diameters of the images of the stars, all of which rest on the magnitudes determined at the Harvard Observatory for the stars of the sequences. For very faint stars, important assistance was rendered by Seares, of the Mount Wilson Observatory. The northern Selected Areas were published first.[37] After the death of Kapteyn in 1922, the extension of his Plan of Selected Areas to the southern sky was carried forward by his successor, Dr. P. J. van Rhijn.[38]

Photovisual Photometry.—The determination of photometric and photographic magnitudes by no means exhausts the subject of stellar photometry. A study of all the radiant energy of the star is needed. The difficulties of even a visual photometry have been many, and a perfect agreement among different investigators is not to be expected, as is shown by a comparison of the scales of the Harvard and Potsdam visual photometries.[39] The chief factor in causing such diversity is color, but even in the case of stars of the same color, no absolute accordance can be expected with different observers and instruments. The wide divergence between the photographic and photometric scales is also largely due to color,

[37] H. A., **101**, 1918.
[38] H. A., **102**, 1923; **103**, 1924.
[39] H. A., **64**, No. 4, 1912.

and consequently, to the portion of the spectrum involved. A complete photometry would include the star's radiations of all wave lengths independently. Such a photometry may be effected by some form of thermocouple, but such a method could not be used for faint stars at present. Visual photometry attempts to measure the amount of the radiation which gives the sensation of light. Photographic photometry shows the intensity of those radiations revealed by the ordinary photographic plate. The two differ widely in the spectral regions concerned. In the Draper Catalogue magnitudes were given derived from measures of the photographic intensity of the spectrum near the line G. The magnitudes thus obtained differ from other photographic magnitudes.[40]

It was early suggested that the many advantages of photographic processes might be utilized in photometry by the use of a suitable combination of color screens and plates, the effect of which would be to yield a scale of magnitudes comparable to visual magnitudes. Such magnitudes are known as photovisual. In connection with her work on the North Polar Sequence, Miss Leavitt obtained some photovisual magnitudes by the use of isochromatic plates and yellow screens, but the results then obtained were not on an independent and absolute scale, and were only accepted as provisional.[41] King has made some interesting investigations in this line. As in other investigations, he employed the method of out-of-focus images, using the 8-inch Draper and the 10-inch Metcalf telescopes. Plates stained with erythrosine, or commercial isochromatic plates, were employed, light reaching them through an intensely yellow screen (dyed with Rapid Filter Yellow) which cut off the blue end of the spectrum. Polaris was photographed on each plate as a standard, and corrections were made for its variation in light. The magnitudes of 24 stars were obtained in this manner. The results would, of course, be altered numerically by changes in the screen or the

[40] H. A., 27, 1890.
[41] H. A., 71, 142, 1917.

plates, but, as King points out, they constitute a standard in themselves.[42]

King later extended his study of photovisual magnitudes to include 100 bright stars. The observations were all made with the 8-inch Draper telescope. The same color screen was used, with plates similar to those previously employed. There are no large differences between the completed photovisual magnitudes and the corresponding photometric magnitudes, the mean difference for the 100 stars being ± 0.07 magnitude. These differences, however, become less as the stars become more red, implying that the photovisual standard is nearer than the photometric to the red end of the spectrum. King's method gives an independent determination of color index, numerically somewhat larger than that derived from visual photometry, but on a definite scale.[43]

Miscellaneous Results.—In addition to the visual and photographic photometry already described, a great number of magnitudes of stars have been determined in connection with other problems. In the Henry Draper Catalogue of stellar spectra, both photometric and photographic magnitudes are given. The former, when not derived from Harvard Annals, **50** and **54**, are Bonn and Cordoba Durchmusterung magnitudes reduced to the scale of the Harvard Photometry; but for stars south of $-62°$ the photometric magnitudes were derived from the Cape Photographic Durchmusterung by the application of corrections depending on the spectral class. The photographic magnitudes were also obtained, in some cases, indirectly from existing catalogues.[44] For the extensions of the Henry Draper Catalogue only photographic magnitudes are given. They are obtained through comparison with a Standard Region, a Selected Area, a sequence of the Astrographic Map, a variable star sequence, or the North Polar Standards.[45]

[42] H. A., **81**, No. 4, 1919.

[43] H. A., **85**, No. 3, 1923.

[44] H. A., **91** to **99**.

[45] H. A., **100**, No. 1, 1925; No. 2, 1926; No. 3, 1927.

Photometric problems still form a large part of the program of the Observatory. Two of the major researches now occupying much of the time of the Observatory are extensive surveys of the Milky Way for the discovery and investigation of variable stars, and a systematic determination of photographic magnitudes on a uniform scale. Another phase of photometry that has been developed at Harvard during the past six years is the spectrophotometric work to which more extended reference is made in the chapter devoted to spectroscopy.

CHAPTER XII

SPECTROSCOPY

The spectroscope has been surpassed only by the telescope in its influence on the development of astronomy. Without its power of analysis, little would be known of the real nature of sun or stars. Although Fraunhofer pointed out the presence of dark lines in the solar and stellar spectra during the early part of the nineteenth century, the significance of these lines was not made clear until 1860 and later, largely through the labors of Kirchhoff and Bunsen. It is not strange, therefore, that little or no attention was given to the subject of spectroscopy at the Harvard Observatory during the administration of the Bonds, 1839 to 1865. Winlock's chief interests, 1866 to 1875, also lay in other directions, although he made spectroscopic observations of the sun at times of total eclipse, as described elsewhere.

Visual Spectroscopy.—Astrophysical problems did not become of primary importance in the programs of the Observatory until 1877 when Edward C. Pickering, a physicist, became director. Great advances in stellar spectroscopy were destined to be made by photographic methods, but these were not begun at the Harvard Observatory until 1882. Meanwhile, by the use of a direct-vision spectroscope with the large refractor, and with other telescopes, rapid surveys were made of large numbers of stars for the detection of objects having peculiar spectra. A large list of such objects was published, and it was pointed out that the long period variables could be readily found by the peculiarities of their spectra. The results obtained were interesting and valuable, but visual observations soon gave way to photographic methods.

Early Photography of Spectra.—The characteristic lines of the solar spectrum had been photographed as early as 1842; but although Huggins made experiments in 1863, in the hope of obtaining photographic spectra of stars, no characteristic spectral lines were shown on his plates.[1] Dr. Henry Draper, an amateur astronomer of New York, was the first to obtain, in 1872, the photographic spectrum of a star showing clearly the spectral lines. Dr. Draper's spectroscopic studies were brought to an end by his death in 1882. As a memorial to his life and work, Mrs. Draper, his widow, established a department of stellar spectroscopy at the Harvard Observatory, which she supported with large gifts during her life and generously endowed at her death. The investigations thus carried forward under the direction of Mr. Pickering became known as the Henry Draper Memorial. It was this generous support, much needed at that time, which enabled Pickering to carry out spectroscopic researches on an unprecedented scale, especially the classification of the spectra of great numbers of stars. The results of these investigations have been of almost incalculable value in the development of modern astronomy.

The pioneer experiments of Fraunhofer had been made with an objective prism, and later Secchi had used it in his visual observations of the spectra of about 4000 stars; previous to 1885 observers in general had made use of the slit spectroscope in their attempts to photograph stellar spectra. Pickering returned to the use of the objective prism for stellar work. For spectroscopic observations of such an object as our sun a slit spectroscope is required, but for stars, which appear as points even in a telescope, no slit is necessary. The first investigation of importance was undertaken with an 8-inch photographic doublet, in front of which was placed a prism having a clear aperture of 8 inches and a refracting angle of 13°. Such an apparatus gives on the plate at any instant a narrow broken line, which can be spaced out into a surface, either by

[1] Phil. Trans. Roy. Soc., **154**, 428, 1864; Mem. Amer. Acad., **11**, 179, 1882.

changing the rate of the driving clock, so that it differs by the desired amount from the sidereal rate, or by a slow motion of the plate itself. The resulting spectra were in general about one centimeter in length and showed sufficient details to enable the character and class of spectrum to be determined.

With the plates and methods at first employed, the spectra of stars to about the eighth magnitude could be photographed with an exposure of one hour, and to the sixth magnitude with an exposure of five minutes. Later, much fainter stars were reached with instruments of no greater size but with a prism of smaller refracting angle. For detailed study of the bright stars, the 11-inch Draper refractor, of nearly 13 feet focal length, and the 13-inch refractor of 16 feet focal length were used with one or several prisms, according to the magnitude of the star. For a few of the brightest stars, spectra have been obtained four inches in length, showing hundreds of lines. Various other instruments have been used for special problems.

The objective prism offers many advantages over the slit spectroscope but has certain disadvantages. Less light is lost, where all the light is of the utmost importance. Also, many spectra can be photographed at the same time and on the same plate. On the other hand a comparison spectrum is difficult to obtain. An absorbing medium of some nature was early tested. Perhaps the best material yet found is neodymium chloride, but the results are not entirely satisfactory. Spectra obtained with the slit spectroscope, with the accompanying comparison spectra of known substances, have undoubted advantages in the determination of wave lengths, of the motions of stars in the line of sight, and in other ways.

The First Draper Catalogue.—The first Harvard catalogue of stellar spectra contained a classification of the spectra of 10,351 stars north of declination $-25°$. Few stars brighter than the sixth magnitude were omitted. The spectrum of each star was in general photographed several times, in all cases with the 8-inch doublet and objective prism. The cata-

logue was called the Draper Catalogue of Stellar Spectra.[2] It seemed necessary at the beginning to make use of an empirical classification. Especial attention was given at first to the four spectral types of Secchi; but it soon became evident that a much more detailed classification was needed, and the letters of the alphabet were adopted. All stars showing the same characteristics were grouped under the same letter. To stars of Secchi's Type I were assigned the letters A to D; to those of Type II, the letters E to L; to Type III, the letter M; and to Type IV, N. Nearly all, if not all, of these letters are used in the Draper Catalogue, but a number of them were rejected later. For example, the letter C was later given up because an apparent duplicity in the lines which it represented was found to be due to the poor quality of the photographs concerned. Also, in certain cases, two groups were formed where but one was needed. For example, stars really of the same class were at first placed under E and G; but E was later rejected since apparent differences between the groups were shown to be in the photographs but not in the stars. These omissions and changes in the order of certain letters to correspond with the probable life history of the stars caused the final arrangement of the letters to appear somewhat grotesque. To change the letters once assigned to stellar groups would cause confusion, however, and the order of the alphabet is not important, since the letters simply serve as symbols.

No subdivisions of the classes represented by the different letters employed are given in this early Draper Catalogue. In a few cases for the fainter stars an interrogation mark (?) is used to indicate doubt, and even when it is not employed occasional uncertainties exist, due principally to the inclusion of stars too faint for exact classification on the plates then available. The work of measurement and classification was done by Mrs. W. P. Fleming under the direction of Mr. Pickering. During the progress of the work it became evident that

[2] H. A., 27, 1890.

stars of the different classes do not fall into distinct groups, or types, but tend to pass insensibly from one class into another. In addition to the spectral class, the Draper Catalogue gives photographic magnitudes; and, in Table II, the hydrogen lines of shortest wave length visible, the intensity of the Fraunhofer K line, 3934, and the presence or absence of the F line, 4861. A discussion of the plates and methods used and the results obtained in the Draper Catalogue was published later.[3]

Miss Maury's Pioneer Analyses of Spectra.—Early in the progress of the Henry Draper Memorial, Pickering planned a study of the spectra of bright stars with as much detail as the equipment of the Observatory would furnish. With the 11-inch and 13-inch telescopes, each star was usually photographed near the center of a plate, and the number of prisms and the exposure depended upon the requirements in each case. One or more additional spectra often appeared, however, on the same plate. To Miss Antonia C. Maury was assigned the discussion of the photographs made in Cambridge, including all bright stars north of declination $-30°$. The work was begun in 1888 but not completed until 1895 or 1896. About 4800 photographs of 681 stars were examined, all made with the 11-inch telescope by the use of from one to four objective prisms. This telescope was originally constructed for visual observations by Dr. Draper, but had been fitted to photographic work by the addition of a correcting lens. Pickering considered it of primary importance that each observer should group together all stars having similar spectra, without especial consideration to theory which could better be discussed later. Miss Maury preferred not to follow the classification of the Draper Catalogue, finding it inadequate for her purpose, and advanced a new and elaborate classification of her own. Her nomenclature is logical, and, with some modifications and extensions, might well have met the needs of astronomers

[3] H. A., 26, Part 1, 1891.

had it been generally accepted. It is evident, however, that one classification is better than several, and the international acceptance provisionally of the revised Draper classification makes it desirable to translate other systems into it. This is simple, in the case of Miss Maury's work, as is well shown in Table XV, in Harvard Annals, **28**, page 145.

In order to determine the wave lengths of lines in stellar spectra, the solar spectrum was photographed with the 11-inch telescope, using a 15-inch reflecting telescope as a collimator. The stellar spectra obtained with four prisms could then be compared directly with the solar spectrum, both being on the same scale.

Miss Maury was provided with plates made by the use of three or four prisms for the detailed study of the brighter stars, but for purposes of classification she employed uniformly plates made with one prism, which were more comparable. The classification was made to depend on the appearance as well as the position of the lines. Since great differences occur in the density of the photographic spectra, and hence in the appearance of the lines, a comparison of a considerable number of photographs was often made before the classification was decided.

It had already been shown that for the most part stellar spectra could be arranged in a series, and that this series probably corresponded to some plan of development. Miss Maury was of the opinion that a simple series was inadequate to represent all the peculiarities which were present, and that it would be more satisfactory to assume the existence of collateral series. These, called "divisions," were designated by the letters a, b, and c, characterized by varying degrees of haziness, width, and intensity of the lines. Miss Maury divided the stars according to their spectra into 22 main groups, and gave a detailed description of each group and its subdivisions, and of typical stars. Translated into the nomenclature of the Draper Catalogue, the 22 groups of Miss Maury fall under the letters, B, AB, A, AF, F, FG, G, K, M, N, and O,

a result which appears more in harmony with the later Draper classification than the early Draper Catalogue. Miss Maury gave tables showing the identification, distribution, and intensities of the solar lines found in the stellar spectra of her groups from VI to XVIII, corresponding in the Draper classification to B, A, F, G, K, and M. Elaborate notes and comments on the spectra of the stars were given, which have proved of much value to special students.

Miss Cannon and the Draper Classification.—In the furtherance of Pickering's plans, during the years 1891 to 1899, 5961 photographs of the spectra of 1122 southern stars and a few northern stars were obtained at the Arequipa Station of the Observatory. They were made with the 13-inch Boyden telescope of 16 feet focal length, with the use of from one to three prisms. The dispersion of these prisms is such that the distance on the plates from $H\epsilon$ to $H\beta$ is 2.24, 4.86, and 7.43 centimeters, for one, two, and three prisms, respectively. The discussion of these plates was intrusted to Miss Annie J. Cannon.

Miss Cannon found it convenient to adopt the notation of the Draper Catalogue, to which had been applied some modifications suggested by the experience of Professor Pickering and Mrs. Fleming. Miss Cannon's method of procedure was to place all the plates in large groups corresponding to the classes B, A, and so forth. Second type stars were placed under Group G, and a detailed study of these was first undertaken, which resulted in various extensions and subdivisions. This process was extended to all the classes. In course of time all the classes and their subdivisions became so definitely established and so clearly visualized by Miss Cannon, that she needed only to glance at a photographic spectrum in order to determine its proper classification.

In any such system the presence and appearance of certain lines form the basis of the classification. Most important to be considered are the well-known hydrogen series, nearly

universally present, extending from $H\alpha$ to $H\upsilon$; the rare but nteresting series found by Pickering in the spectrum of ζ Puppis, first attributed to hydrogen and later to helium; the "Orion" lines, largely due to helium, but also to other elements; the solar or metallic lines; and, in comparatively ew cases, bright lines of one kind or another. Miss Cannon ound it inadvisable to adopt the "divisions" a, b, and c, considered necessary by Miss Maury, but instead prepared elaborate remarks regarding the appearance of the lines whenever needed.

As few changes have occurred in the Draper classification since the publication of this investigation by Miss Cannon, a brief outline of its chief characteristics may well be given here. From B to M the Draper classification represents clearly a single, continuous series. The vast majority of all stars all into this series. For each letter employed, decimal subdivisions follow to indicate successive variations leading to he next spectral class. For example, B, or Bo, is used to represent spectra in which some of the "Orion" lines are as ntense as the lines of hydrogen. Nine subdivisions, B1 to B9, are provided and may be used leading to the next class, A. These steps indicate gradual decreases in the intensity of the "Orion" lines and increases in the intensity of the hydrogen ines. When Ao is reached, the "Orion" lines are generally absent, the hydrogen lines very intense, and the solar lines aintly present. The main classes of the whole series, as used by Miss Cannon in this work, may be seen best in tabular orm.

P. Gaseous nebulae. Only one example in the catalogue.
Q. Peculiar spectra with bright lines. Three examples.
O. Fifth type. Bright bands on a faint continuous background.
B. Orion lines and those of hydrogen almost equally intense.
A. Hydrogen lines very intense. Disappearance of helium and beginning of solar lines.
F. Hydrogen lines still intense and many solar lines.
G. Solar type, spectrum closely resembling that of the sun.
K. Hydrogen lines less marked, K line intense.
M. Banded spectra.

In general B and A correspond to Secchi's Type I, F is intermediate between I and II, G is II, K is intermediate between II and III, and M is III. The position of Class O in the series evidently preceded that of Class B. The relation of P and Q to the other classes was less evident, but since they appeared to be more nearly related to O than to any of the others, they were placed before O. The spectra of Class O are divided into the subdivisions Oa, Ob, Oc, Od, Oe, and Oe5. In Oe5 all the lines are dark and the type of spectrum approaches the B stars closely. A special description of each Md star is furnished. A table is first given containing the spectra of the 1122 stars in the order of the above classification, and another table in which they appear in the order of right ascension. Detailed notes cover the peculiarities of individual stars.[4]

The classification of bright stars, northern by Miss Maury and southern by Miss Cannon, was given in Harvard Annals, **28.** In the work on the northern sky, many stars of magnitude 4.0 to 5.0, and a few brighter than 4.0, were omitted: 1726 photographs of these stars were made later than 1904 with the 11-inch telescope and the use of one prism. The classification of these stars was carried out by Miss Cannon, on the same system, from O to M, as that of Harvard Annals, **28,** Part 2. Class N was added for stars like U Hydrae having a wide absorption band near wave length 4738. This catalogue consists of 1477 stars, and additional tables are given of stars having special peculiarities.[5] A work similar to the preceding for the extension of the spectral classification to fainter stars in the southern sky was also done by Miss Cannon. It forms a supplement to Harvard Annals, **28,** Part 2, and contains 1688 stars.[6]

The Henry Draper Catalogue.—One of the largest and most important investigations ever carried out at the Harvard

[4] H. A., 28, Part 2, 1901. For later modifications of the classification, proposed by the Committee of the International Astronomical Union on Spectral Classification, see Trans. Int. Astron. Union, 1, 97, 1922.

[5] H. A., 56, No. 4, 1912.

[6] *Ibid.*, No. 5.

B0

B8

A0

F0

G0

K0

M1

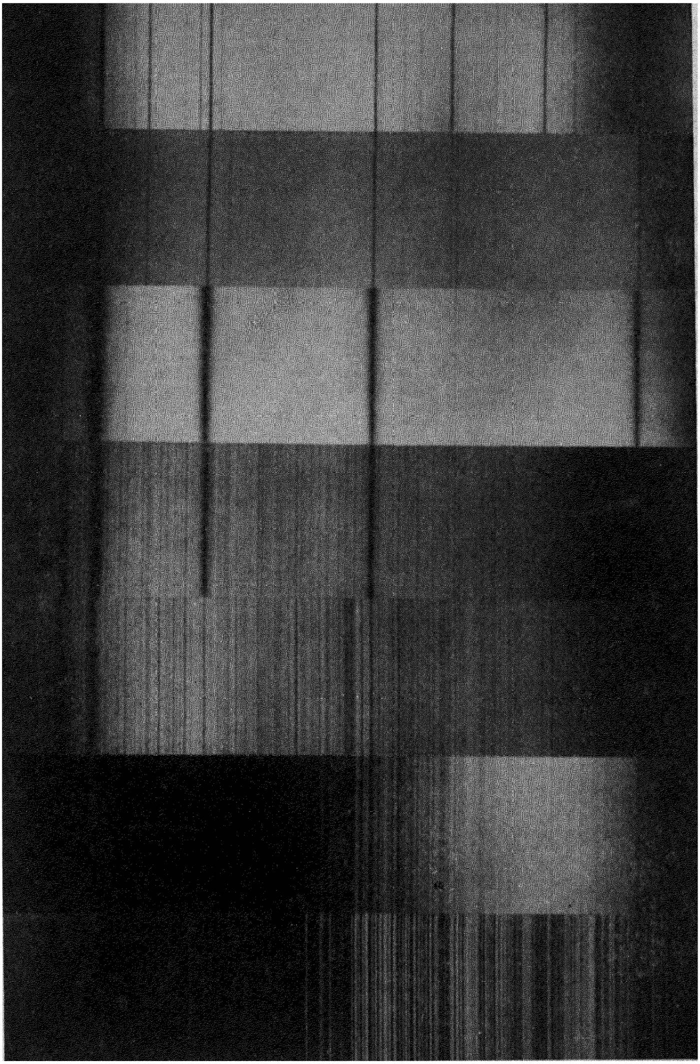

PLATE XV.—TYPICAL STELLAR SPECTRA: B0, ε ORIONIS; B8, RIGEL; A0, SIRIUS; F0, CANOPUS; G0, CAPELLA; K0, ARCTURUS; M1, BETELGEUSE.

(*Facing page 156*)

Observatory is the Henry Draper Catalogue of stellar spectra, which fills nine volumes of the Annals. This great work had its beginnings in the early Draper Catalogue of Harvard Annals, **27**, and in its extension to all the bright stars (H. A., **28**). Its execution was possible only by the mass of material which had been accumulated through many years of photographic work with different telescopes and prisms, both at Cambridge and Arequipa. It was the culmination of the life efforts of Edward C. Pickering, and the center of his interests during the closing years of his life.

All the classifications in the Henry Draper Catalogue were made by Miss Cannon, whose long experience in spectroscopic observations made her eminently fitted for the work. Also, the fact that all the classification was done by one observer brought a uniformity into the results which could hardly have been expected if several observers had taken part.

The spectra of bright northern stars, which had been classified by Miss Maury and published in Harvard Annals, **28**, Part 1, were reclassified by Miss Cannon in order to bring them into harmony with the remainder of the Henry Draper Catalogue. The classification of additional northern stars to the fifth magnitude was taken from Harvard Annals, **56**, No. 4. For all southern stars brighter than the sixth magnitude the results already published by Miss Cannon in Harvard Annals, **28**, Part 2, and in Harvard Annals, **56**, No. 5, were used. In all other cases new classifications were made. Miss Cannon had several assistants for the laborious identification of all the objects and for other details of the investigation. The classification of the stars in the catalogue was begun in October, 1911, and was practically finished by the end of September, 1915, although a few stars were added later. The total number of stars whose spectra are included in the catalogue is about 225,000. The instruments and methods have already been described. The classification here used is the same, with a few additions and modifications, as that in Harvard Annals, **28**, Part 2. The main series extends from P to M. Two classes,

R and N, were added, characterized by carbon and cyanogen bands. Class S was later adopted by the International Astronomical Union to designate spectra of a peculiar type consisting of bright and dark bands. The relation of Classes R, N, and S to the main linear series is somewhat uncertain, but they may represent branches from it. The term "Pec." was used in rare cases for spectra whose characteristics did not permit them to be assigned to any known class. "Con." was used to represent spectra which appeared to be continuous. Each of the volumes contains a full page frontispiece illustration. The nine plates show spectra of the different classes and with varying dispersions, giant and dwarf spectra of the same class, and portraits of Henry Draper, Mrs. Draper, and Edward C. Pickering. Mr. Pickering died on February 3, 1919, when only three volumes had been published. Thereafter Miss Cannon supervised the publication of the remaining six volumes and to her is due the successful completion of the work.[7]

The Henry Draper Extension.—A discussion of the material of the Henry Draper Catalogue revealed inequalities in different parts of the sky. In general, owing to better conditions at Arequipa, fainter stars were included in the southern sky than in the northern. This difference amounted to a magnitude, the catalogue as a whole being complete to about the eighth magnitude for northern stars, and to the ninth magnitude for southern stars.

To balance the survey somewhat, and especially to explore interesting areas in the Milky Way, Shapley decided, in 1923, upon an extension of the Henry Draper Catalogue.[8] He did not plan a uniform extension, but a survey of those regions of most importance in his studies of stellar distribution. It was estimated that about a million unclassified spectra were available on plates already included in the Harvard collection. The first region selected for the Extension was one covered by a

[7] H. A., **91** to **99**, 1918 to 1924.

[8] H. C. 278, 1925; H. A., **100**, No. 1, 1925.

plate made with the 10-inch Metcalf triplet, with small dispersion, 2.23 mm from Hβ to Hϵ, but of excellent definition. This plate, covering an area of about 80 square degrees with a center at 20^h, $+37°$, in the star cloud in Cygnus, contained the spectra of 4490 stars, of which 498 had been included in the Henry Draper Catalogue and 3992 were added in the Extension. The classification, as well as the determination of the photographic magnitudes, was made by Miss Cannon. In a discussion of the results of this Extension, Shapley is led to the following conclusions, given here in a very condensed form: 1. The limiting magnitude for completeness is just below the eleventh, although fainter stars are included. 2. The Henry Draper Catalogue for this region is practically complete to magnitude 8.5. 3. In both catalogues Class M stars are classified half a magnitude fainter than those of earlier types. 4. No new stars of Class O were found, and none marked "Pec." 5. The international scale of magnitudes was used, and a correction found for the magnitudes in the Henry Draper Catalogue. 6. There was good accordance with the Henry Draper Catalogue, but M stars were placed a trifle later, and other types a trifle earlier in the Extension. 7. Class K stars were relatively less numerous in the Extension.

Two other sections of the Extension have been carried forward by Miss Cannon, one containing 3000 additional spectra, and the other, 5000 spectra.[9]

Discussions of the Henry Draper Catalogue.—A large number of investigations related to the work of the Henry Draper Memorial have been carried out at the Observatory. A volume of such studies was published in 1912, although some of the numbers included had been in print for several years. In his discussion of the early Draper Catalogue, Pickering had made an investigation into the distribution of stars of different spectral types, from which he concluded that the Milky Way consists largely of stars of the first type, Classes

[9] H. A., 100, Nos. 2, 3, 1927.

B and A. Later, a grouping of 32,197 spectra confirmed his previous conclusions and also indicated that stars of the second and third types were distributed nearly uniformly over the whole sky.[10]

Pickering also made a special study of B stars. Using the early Draper Catalogue and all other data available at that time he compiled a list of 803 stars of Class B, and made a discussion of their distribution. He found that a large proportion of these stars are in the constellations Orion and Argo, a fourth of them being contained in a region having only one fiftieth of the area of the whole sky. He reached the conclusion that nearly all B stars are comparatively bright. His tabulated results indicated that, while among stars brighter than magnitude 2.5 one out of four is a B star, among stars of the sixth magnitude only one in twenty is of that class. He predicted that few if any B stars would be found fainter than the seventh or eighth magnitude.[11]

More recently, Dr. Shapley, in association with Miss Cannon, has made important contributions to this subject, using the enormously increased data provided by the Henry Draper Catalogue. Shapley and Miss Cannon show the relation between spectral type and magnitude.[12] The results are well brought out by the use of diagrams. A table giving the frequency of spectral divisions for successive magnitude intervals leads to striking results. The percentage of stars of classes A, F, K, and M remains about the same for all magnitudes up to the ninth. For B stars there is a marked decrease as the magnitude increases, and for G stars, a still more marked increase. The results differ somewhat from those obtained by Pickering, but the material discussed was about twenty times as great and, in some respects, of better quality, than that used by Pickering.

Later, Shapley and Miss Cannon called attention to the existence and influence of the local system of stars, having its

[10] H. A., 56, No. 1, 1912.
[11] *Ibid.*, No. 2.
[12] H. C. 226, 1921.

quatorial plane inclined about 10° to that of the Galaxy. The distribution of 2450 bright A stars was shown on an Aitoff hart of equal area projection. The investigation appeared to onfirm the existence of the local cluster, but left many problems or further study.[13]

Miss Leavitt discussed the relation of spectral class to nagnitude in the Harvard Standard Regions. The problem aised was: do stars on the whole grow redder with increasing aintness? If so, is it due to a relative increase in the number of ate type stars, or to some other cause, such as an absorbing nedium? Miss Leavitt concluded that the stars taken altogether from the seventh to the eleventh magnitude appear edder with increasing faintness.[14]

In a discussion of the distribution of stars of spectral class B, Shapley and Miss Cannon have shown that the fainter B stars, o magnitude 8.25, are confined to a narrow belt along the galactic circle, the bright stars alone indicating the existence of a local cluster not coincident with the Galaxy. Four diagrams were given containing the positions of all such B stars eferred to the galactic plane, for the groups, brighter than .26, 5.26 to 6.25, 6.26 to 7.25, 7.26 to 8.25, respectively.[15]

Shapley also made a discussion of the spectral constitution of he nearer parts of the Milky Way; 11,030 stars are included in he discussion, which is well illustrated by diagrams. Many nteresting conclusions are derived, including the following: tars of Classes A and K predominate in the nearer parts of the Milky Way (100 to 500 parsecs), in so far as the stars of ordinary atalogues are concerned; dwarf K stars in this region would e too faint to appear on the photographs; the results are nodified by various obscure areas and the great rift in the Milky Way; and, especially, a remarkable uniformity exists, xcept in certain details, in the galactic distribution of all pectral classes except M.[16]

[13] H. C. 229, 1922.
[14] H. C. 230, 1921.
[15] H. C. 239, 1922.
[16] H. C. 240, 1922.

Somewhat later, Shapley and Miss Cannon discussed the distribution of stars of Class M in the Henry Draper Catalogue. Practically all such stars are giants. The following conclusions were made, here given in a somewhat condensed form. 1. For stars of Class Mb, brighter than the eighth magnitude, no galactic concentration is shown; but Ma stars are more numerous by 30 per cent between latitudes -10° and $+30^\circ$. 2. For stars fainter than the eighth magnitude both Ma and Mb stars are concentrated to the Galaxy. 3. The apparent galactic concentration of Ma stars is based on insufficient data. 4. Variables of Class Md appear to be concentrated to galactic latitude -20°, but there is a marked asymmetry in longitude. 5. In the direction of Taurus, there is one half, and in the opposite direction of Sagittarius, twice the average number of variables. 6. The fainter stars of Classes Ma, Mb, and Mc show a marked preference for the region of Sagittarius. 7. There are 1500 giant M stars within 500 parsecs of the sun, and at least 3000 within 800 parsecs.[17]

Shapley continued his investigation by a study of the "Spectral Class, Apparent Magnitude, and Galactic Position for Stars of the Henry Draper Catalogue." Counts were made of the stars in selected fields, each with an area of 100 square degrees. The relation between numbers of B and M stars and galactic latitude was represented by diagrams. Among the results shown are the predominance of the A and K stars in the Milky Way, and the lack of galactic concentration of F and G stars brighter than magnitude 8.25[18]

Dr. Shapley later gave his attention to the density of stars in space, using data derived from the Henry Draper Catalogue, and from current investigations of the average absolute magnitude of the spectral classes. The chief results are summarized in the accompanying table, in which the first and second columns give the spectral division and the spectral classes within the division, and the third column, the average number of

[17] H. C. 245, 1923.
[18] *Ibid.*, 248.

stars brighter than visual magnitude 8.25 in 100 square degrees. The fourth column gives the distance in parsecs throughout which the stars of each type have been collected; they vary considerably with type.

Division	Spectral Classes	Surface Number	Distance Limit	Space Number
B	B0-B5	29.7	880	4 4
A	B8-A3	96.9	340	250
F	A5-F2	18.7	140	680
G	F5-G0	26.0	70	7600
Giant K	G5-K2	69.0	350	160
Giant M	K5-Mc	17.5	430	22

Dr. Shapley and Miss Cannon comment on the tabulation:

The values in the last column are the numbers of stars in a million cubic parsecs. On account of the amount of material involved in these counts, it is not probable that local aggregations have seriously affected the results. The tabulation does not take account of the Cepheids, the giants of Class G, the abnormally faint A stars, nor the dwarf K and M stars. Stars of these last two classes are probably much more numerous per unit volume than dwarf stars of Class G. As a first approximation, the giant G stars may be taken as one-half as numerous as the giants of Class M.

Perhaps the most interesting deduction from these results is that for every Class B star that is in the stage of development represented by the Orion and Scorpius clusters, there are about five giant M stars and seventeen hundred dwarfs like our Sun. This conclusion should be of some significance in considerations of stellar evolution.[19]

Dr. Shapley and Miss Cannon have also made a summary of the studies of stellar distribution previously carried out, with important additions and conclusions. Diagrams were used to illustrate the galactic distribution of the B stars, the concentration of stars of all classes toward the galactic circle, and the apparent frequency of various spectral classes. The distances of the stars and the number of stars in unit volume are again analyzed.[20]

[19] H. B. 792, 1923.

[20] Proc. Amer. Acad., **59**, No. 9, 1924; H. Repr. No. 6, 1924.

Miscellaneous Problems.—During the development of the Henry Draper Memorial, spectrum plates of the whole sky were made with lenses of different sizes and objective prisms of different angles. With a large lens and small dispersion the spectra of stars as faint as the eleventh magnitude have been made. Among the many thousands of spectra photographed, a very large number of peculiar spectra were found by careful examination of the photographs, and it is probable that few permanent objects of this character escaped detection. By means of bright lines or other spectral peculiarities a large number of novae, variable stars, and other special objects were discovered. The classification and discussion of these objects were carried on chiefly by Mrs. Fleming, under the direction of Pickering. After the death of Mrs. Fleming in 1911, the work was completed by Miss Cannon and others. Since the distribution of such objects generally bears some relation to the Milky Way, the catalogues containing them, in addition to the right ascension and declination, furnish also the galactic longitude and latitude. Separate tables are given for novae, gaseous nebulae, fifth type stars, stars having bright hydrogen lines, spectroscopic binaries, Algol and other variables, stars of spectral class N, and other rare spectral types. The work is illustrated with two plates giving examples of spectra of the above types.[21]

A classification of the spectra of double stars has been provided by Miss Cannon, who examined 745 such objects on the Harvard plates. The class of spectrum is given either for the two components together or for each separately. When the distance between the components is less than 10″, it is difficult to classify the spectra of the components separately on plates made with the objective prism. Special devices were tried to minimize this difficulty.[22]

The Draper spectral classification depends on photographs made with the objective prism. At other observatories, for

[21] H. A., **56**, No. 6, 1912.
[22] *Ibid.*, No. 7.

the most part, the slit spectroscope has been used. Miss Cannon made a comparison of the results obtained by the two instruments. Spectrograms made with slit spectroscopes were loaned to the Observatory by the Directors of the Yerkes, Lick, and Allegheny Observatories. The number of plates was 20, 48, and 35, respectively. The stars were independently classified by Miss Cannon on both kinds of plates, and though there were some striking differences of detail, the resulting classifications showed fairly satisfactory accordance. A few differences as large as 10 spectral subdivisions, or a whole class, occurred, but for 51 of the stars there was no difference. A comparison was also made of the classifications made by Kohlschütter at Mount Wilson and Miss Cannon at Cambridge, with equally good accordance.[23]

The Spectroscopy of Novae.—Spectral studies regarding novae, or new stars, have received considerable attention at Harvard. Early in the history of the Henry Draper Memorial it was found by Mr. Pickering and Mrs. Fleming that on a plate containing hundreds of spectra such objects could be readily detected by their striking spectral peculiarities, especially the bright lines. Many novae were found in this way, as well as many variable stars. Announcements and studies of novae are found in various Circulars.[24] Miss Cannon made detailed investigations regarding the peculiarities and changes in the spectra of Nova Persei, No. 2, and Nova Aquilae, No. 3. The second of these is of special interest, since the spectrum could be studied through five periods in the history of the star: 1. Before the outburst on June 7, 1918, the spectrum probably some division of Class A. 2. Rapid increase in brightness, numerous dark lines. 3. Near maximum, immediately following which the spectrum changed into the typical nova form having broad, bright hydrogen lines accompanied by dark lines; many changes during decrease in light. 4. Oscillatory

[23] *Ibid.*, No. 8.

[24] H. C. 42, 1899; 56, 57, 1901; 176, 1912; 209, 1918; 289, 1925; 295, 1926.

period with frequent changes in brightness and spectrum. 5. A slow and fairly uniform decrease in light, with the nebular band 4363 the brightest portion of the spectrum.[25]

Another interesting object of this class was Nova Pictoris, discovered in 1925. A long series of spectrum plates of this star was made at Arequipa from a study of which Davidovich concluded that Nova Pictoris followed the normal development of a new star, but that the spectral changes were unusually slow.[26]

Double Star Spectroscopy.—For nearly two centuries visual double stars have been observed by astronomers. Several thousands are known, the majority of which are physical doubles, or binary systems. The period of revolution of the components of such doubles is long, from a few years to hundreds of years. Since the development of the spectroscope, a large number of spectroscopic binaries have been found. Such stars appear single even in a large telescope, since the components are too close to be separated visually, but with the slit spectroscope the radial velocity is shown to be variable, indicating that the star whose spectrum is observed is acted upon by a second body. A comparison spectrum must be used in the observation of such stars, a process which has been found difficult with the objective prisms employed at the Harvard Observatory. Certain close binaries, however, have both components bright and revolving in such a plane and with such a velocity that the spectral lines appear on the plates alternately single and double. When one component of the system is approaching the observer, in its revolution about the common center of gravity, and the other component is receding, the corresponding lines of the two stars are separated; at other times they are single. Pickering was the first to discover a star of this sort, ζ Ursae Majoris, in 1889. Its period, at first thought to be 52 days, was later shown by Vogel

[25] H. A., **56**, No. 3, 1912; **81**, No. 3, 1920.
[26] H. B. 823, 826, 835, 839, 1925.

to be 20.5 days. Later in the same year Miss Maury found a similar star, β Aurigae, with a period of about 4 days. A third, μ^1 Scorpii, was found at Arequipa in 1896, by Bailey, having a period of a little less than 35 hours. A few other such objects have since been found, but the number discovered at this Observatory is small.[27] A discussion of a long series of photographs, covering many years, of μ^1 Scorpii and V Puppis has been made by Miss Maury, who finds them to be among the spectroscopic binaries having the highest radial velocity, the mean amplitudes being, respectively, 480 and 604 km. They are similar in having high velocity, low eccentricity, small orbit, and great mass; μ^1 Scorpii is an eclipsing variable of the β Lyrae type, with small range.[28]

Spectroscopic Parallaxes.—The determination of the distances of the stars presents one of the most difficult problems in astronomy, and the method of spectroscopic parallaxes renders powerful assistance. The first suggestion that a relation exists between the intensity of certain spectral lines and the absolute magnitude was probably made by Hertzsprung.[29] Nothing further appears to have been done about it, however, until 1914, when Adams and Kohlschütter, of Mount Wilson, developed the subject independently, carried it forward systematically, and obtained definite results. The presence of thousands of spectrum plates at the Harvard Observatory promised great extensions of this line of research, provided spectra obtained with the objective prisms were suitable for the purpose. In 1916 Dr. Shapley, then at the Mount Wilson Observatory, offered to investigate this matter, and a number of photographs of various spectral classes were sent to him by Pickering. These objective prism spectra were found to be satisfactory. In 1921 Shapley, then Director of the Harvard Observatory, in association with Lindblad,

[27] H. C. 11, 14, 1896; H. A., **28**, 230, 1897.
[28] H. A., **84**, No. 6, 1920.
[29] Zs. f. Wiss. Phot., **5**, Part 3, 1907.

who was also familiar with the recent Mount Wilson methods, determined the absolute magnitudes and distances of 50 stars of types K0 and K2 from a study of Harvard plates. In general, the criteria employed at Mount Wilson were used, giving most weight to the changes with absolute magnitude of the line λ 4215 of ionized strontium, but also using the cyanogen bands, and the lines of hydrogen, calcium, and manganese.[30] A little later Dr. and Mrs. Shapley determined the distances of 87 bright stars of Class K. For stars common to Harvard and Mount Wilson, the differences were satisfactorily small. They reached the conclusion that, in addition to the criteria already in use at Mount Wilson, several other characteristics which had been found promised to extend the usefulness of the Harvard photographs to fainter stars.[31] In later publications Shapley has pointed out that, on account of outstanding errors in existing photometric scales and in individual estimates of brightness, the absolute magnitudes for most classes of stars can be estimated as accurately as the apparent magnitudes are known, and that, for stars fainter than the eighth magnitude, the uncertainties in apparent magnitudes make further refinements in absolute magnitudes of little immediate value for many classes. A table of distances based on the apparent magnitudes and spectral classes as given in the Henry Draper Catalogue furnishes results fairly satisfactory for ordinary statistical purposes. Such a table of mean results for 105,529 stars of that catalogue is given. Spectral parallaxes were also determined by independent methods for several hundred southern stars. The results, when compared with Mount Wilson, indicate a small systematic difference.[32]

Development of Spectrophotometry.—In recent years quantitative methods have invaded stellar spectroscopy, as

[30] H. C. 228, 1921.
[31] H. C. 232, 1922.
[32] H. C. 243, 246, 1923.

they invaded stellar photometry during the previous half century. Much work at Harvard has been directed to the establishment of stellar spectrophotometry during recent years.

Detailed studies of physical conditions in the atmospheres of stars, such as were undertaken by Miss Payne and her associates in 1923,[33] showed at once that real progress must depend upon accurate methods of measurement. The beginnings of Harvard spectrophotometry are to be found in Shapley's note on the intensity of the hydrogen lines in the spectrum of Vega,[34] derived by the same method that has since been used in most of the Harvard investigations in spectrophotometry.

The subject has been vigorously pursued at Harvard, especially by Miss Payne,[35] Hogg,[36] and Dunham,[37] and there can be no doubt that observational stellar spectroscopy has entered upon a new era. Theories that have hitherto ranked as qualitative speculations can now be put to the test, and there is every reason to believe that much of the current uncertainty as to the conditions in the atmospheres of the stars is soon to be dispelled.

[33] H. C. 252, 256, 263, 1924; 287, 1925; 300, 1927; H. Mon. 1, 1925.
[34] H. B. 805, 1924.
[35] H. C. 301, 302, 303, 304, 1927.
[36] H. C. 301, 1927.
[37] H. B. 853, 1927.

CHAPTER XIII

VARIABLE STARS AND NOVAE

THE subject of variable stars has assumed an increasing importance in astronomy. Not only do these stars contribute to our better understanding of the nature of the sun, but also they have recently been recognized as of great value in the interpretation of cosmic problems. Interesting objects on their own account, they appear to have completely escaped detection by ancient astronomers, although several of them are sufficiently bright to be observed with the naked eye. Excluding novae, the existence of a variable star was probably first recognized in 1639, by Holwarda in his observations of *o* Ceti. This star had been seen by Fabricius in 1596, but he probably regarded it as a nova.

Classification of Variable Stars.—Little progress was made in the discovery and observation of variable stars for two centuries, until the subject was placed on a scientific basis by the work of Argelander and Schönfeld. Argelander compiled a list of 18 stars supposed to be variable in 1844, and undertook their observation. In 1854, Pogson published a list of 53 known variables. In 1865, Schönfeld issued a catalogue of 113 variable stars, and, in 1875, one of 165 stars. This was the condition of the problem when the subject was taken up at the Harvard Observatory under the direction of Edward C. Pickering. Previous to his administration no attention had been given to variable stars. In 1880 Pickering published a paper on the dimensions of stars, with special reference to binaries and variables of the Algol type; he discussed the characteristics of such binaries, determined the elements of Algol (β Persei), and pointed out that the period was

subject to change. In this article he first proposed his division of variable stars into five classes. His classification has received long and wide acceptance and nothing essentially better has yet been proposed, although various subdivisions are perhaps desirable.

The system is essentially as follows:[1]

1. Temporary, or new stars, Novae. Example, Tycho Brahe's star of 1572.
2. Long period variables, large range in variation. Example, o Ceti.
3. Irregular variables. Example, α Orionis.
4. Variables of short period, moderate range of variation. Example, δ Cephei.
5. Variables of the Algol type. Example, β Persei, Algol.

Other communications speedily followed, discussing the nature of variations in the light of stars, and the progress of variable star observations.[2]

Amateur Observations of Variables.—Pickering early recognized the desirability of enlisting amateur assistance in the observation of variables. In 1882 he issued a bulletin entitled "A Plan for Securing Observations of the Variable Stars," calling for volunteers. Mr. Pickering thought that the subject would appeal strongly to educated women of leisure. While women have been eminent as patrons of science, and as professional astronomers, it seems rather surprising that among the vast number of observations of variable stars which have been contributed by scores of enthusiastic amateur observers, the number of observations made by women is relatively very small. Nearly all the active observers have been men, usually very busy men. For several years Pickering's reports on the progress of variable star observations were made through the medium of the Proceedings of the American Academy, doubtless from motives of economy.

During a trip to Europe in 1883, Pickering found two unpublished catalogues of observations made by Sir William Herschel, which he also discussed and published in the Pro-

[1] Proc. Amer. Acad., **16**, 1, 1880.

[2] *Ibid.*, p. 257; 370, 1881; H. A., **46**, Chap. 9, 1904.

ceedings.[3] Later, he published in the Annals an "Index to Observations of Variable Stars," designed to give information on the subject for the whole period from 1840 to 1887.[4]

In 1888, Seth C. Chandler, an amateur astronomer, closely associated for many years with the Harvard Observatory, published his first catalogue of 225 variables, which was followed in 1893 by a second catalogue containing 260 stars, and, in 1896, by a third catalogue of 393 stars.[5] These catalogues show how rapid was the development of the subject.

The Harvard Catalogues of Variable Stars.—Meanwhile, at Harvard, much attention was given to variable stars. The first provisional catalogue of variable stars published at the Harvard Observatory, prepared by Miss Cannon, contained 1227 stars, including 509 in the globular clusters.[6] Miss Cannon also prepared a second catalogue of variable stars, including variables in clusters, published in 1907; it contained 1957 stars, and in addition 1791 variables had been found by Miss Leavitt in the Magellanic Clouds, making in all 3748 known variables, 2909 of which had been found at the Harvard Observatory.[7] By the end of 1927 the number of known variables had passed 5000, of which 4106 had been found at Harvard. This very large increase was due chiefly to the introduction of photographic methods. A bibliography of variable stars has long been maintained at the Observatory. It was begun by W. M. Reed, in 1897, but since 1900 it has been developed by Miss Cannon. It now contains about 50,000 entries providing information concerning known or suspected variable stars.

The Naming of Variable Stars.—The nomenclature adopted for the designation of variables is of considerable importance.

[3] Proc. Amer. Acad., **19**, 269, 296, 1884; **20**, 393, 1885; **21**, 319, 1886; **22**, 380, 1887.

[4] H. A., **18**, No. 8, 1890.

[5] A. J., **8**, 81, 1888; **13**, 89, 1893; **16**, 145, 1896.

[6] H. A., **48**, No. 3, 1903.

[7] H. A., **55**, Part 1, 1907.

The system proposed by Argelander is, with some modifications, the one most widely employed. Argelander assigned the letter R to the first variable found in a constellation, as, for example, R Persei, the letter S to the second, and so on to Z. Since his first list contained only 18 stars, this plan seemed simple and satisfactory, but as the number of variables increased it required extension. Additional designations were obtained by doubling the letters, RR to RZ, SS to SZ, and so forth. In this way the number of names for a constellation was raised to 54. This number, however, later became insufficient, and further extensions were made by the use of the letters, AA to AZ, BB to BZ, and so forth, thus adding 280 more, and making in all 334. Even this number has already become inadequate in Sagittarius and Ophiuchus.

In his catalogues, Chandler introduced a method of designating a variable by giving it the number obtained by dividing by 10 the number of seconds in the star's right ascension for 1900. This method is not used at the present time.

A different system, proposed by Pickering, was introduced in the "Provisional Catalogue" of 1903. Each variable was assigned the number, consisting of six figures, which represents the approximate position of the star. The first four figures gave the right ascension for 1900, expressed in hours and minutes, and the last two figures, the declination in degrees. Italics were used for southern stars. For example, the approximate position of S Ursae Majoris for 1900 is $12^h\ 39^m.6 + 61^\circ\ 38'$, and the Pickering number is 123961. The special advantage of this system is that the numbers are readily remembered by the observer who uses them frequently and give at once the position of the stars with sufficient precision in most cases to enable approximate settings of the telescope to be made. It was soon found, however, that the same number occasionally occurred twice or more times, necessitating the addition of the letters a, b, and so forth. This difficulty will continually grow more serious. The system has been

widely used by Harvard observers, and by the large number of amateur observers associated with the Observatory, who have found it well fitted for their observations. Both the Pickering and Argelander designations have been given in most Harvard publications.

Perhaps the best system ever proposed is that of André, who suggested the use in all cases of the letter v to indicate the variable, followed by a number representing the order of discovery, and last by the name of the constellation. Thus, v 25 Persei denotes the twenty fifth variable discovered in the constellation Perseus. This system is capable of indefinite extension, and has been recommended for general use in the Report of the International Astronomical Union for 1925.

Visual Photometry of Variable Stars.—Variable star observations formed a part of the early work of the Harvard Photometry. In forming the lists of stars for observation with the first meridian photometer, in 1879, Pickering included all variables contained in Schönfeld's second catalogue not fainter than 6.5 at maximum. Later in the same research he measured the brightness of the comparison stars for a number of variables.[8]

The same policy was pursued on a much larger scale in later years by Pickering and other members and associates of the Observatory. In connection with the photometric revision of the Durchmusterung, Pickering and Wendell made photometric measures of 166 variable stars during the years 1882 to 1888.[9] At about the same time, H. M. Parkhurst, an amateur astronomer of high ability, began his contributions to the subject. He used the method of Argelander, estimating the variable as equal to one of a sequence of comparison stars, or between two comparison stars, one somewhat brighter, the other somewhat fainter, estimating the intervals in grades. From 1883 to 1891, Parkhurst made a large number of obser-

[8] H. A., **14**, 84, 401, 1884.

[9] H. A., **24**, 251, 1890.

vations of variables and of comparison stars. He also derived light curves, and determined corrections due to moonlight, to the use of shades, and so forth.[10]

During the 20 years from 1892 to 1912, Wendell used the 15-inch refractor with polarizing photometers for refined observations of variable stars of different kinds, in addition to his observations of double stars, asteroids, the satellites of Jupiter, and other objects. His investigations were carried out with extreme care and skill; and the photometers devised by Pickering were capable of yielding results of much accuracy. It is probable that Wendell's are the most precise observations of variables ever made at the Harvard Observatory. His work includes extended observations of variable stars of long period, of Cepheid variables, and of variable stars of the Algol type, and the light curves derived from them deserve the confidence which they have received.[11] In particular, Russell and Shapley used Wendell's work as a basis for the Princeton studies of the orbits of eclipsing binaries.

Standard Magnitudes for Published Observations.—Reference has already been made to the publication in the Annals of some of Sir William Herschel's variable star observations. Desiring to place before the astronomical public in a convenient form the results of early observations of variables, Pickering undertook the reduction and publication of a part of the observations of Argelander, Schönfeld, and Schmidt. The pioneer observations of Argelander, from 1838 to 1867, had been published, but about 4000 later observations appeared likely to remain unpublished, when Pickering undertook their reduction and publication. A careful determination of the value of Argelander's grade was made. It varied in different years but the mean value was about 0.14 magnitude. The comparison stars were measured with the meridian photometer, with the exception of stars too faint, and the magnitude of the

[10] H. A., **29**, No. 4, 1893.
[11] H. A., **69**, Part 1, 1909; Part 2, 1913.

variable for each observation was determined. A somewhat similar investigation was made of Schönfeld's observations of variables from 1853 to 1859, and of Schmidt's observations at Athens from 1845 to 1879. These investigations made available a large mass of material that would otherwise have remained comparatively inaccessible.[12] Schönfeld's later observations, made with great care between 1859 and his death in 1891, lost for a time but afterwards found, were published in Germany. In order to render these results available for the study of periods and light curves, Pickering made a determination of the magnitudes of the comparison stars on the photometric scale.[13]

Visual Observations at Harvard.—A large proportion of the Observatory staff, at one time or other, has made visual or photographic observations of variable stars. Many determinations of the brightness of variables and of their comparison stars have been made with different photometers by Pickering and others, beginning in 1896. The measurements included variable stars of long period, of short period, and of the Algol type.[14]

Visual estimates of the magnitudes of variables were undertaken on a large scale in 1889. An extended investigation was made of 17 circumpolar stars, all north of declination +50°, selected because they were always above the horizon of Cambridge and could therefore be observed at all seasons. The plan included at least one observation a month of each variable, so that the light curves would be known at minima as well as at maxima. A sequence of comparison stars was chosen for each variable, in general, although in one instance a sequence was made to serve for two adjacent variables. A sequence consisted of a group of stars, the successive members of which differed in brightness by a third or a half of a magnitude,

[12] H. A., 33, Nos. 4 to 6, 1900.
[13] H. A., 64, No. 3, 1912.
[14] H. A., 46, Part 2, 1904.

the brightest star being somewhat brighter than the variable at maximum, and the faintest, somewhat fainter than the variable at minimum. Various observers took part in the observations, but the greater part were made by Wendell, Reed, and Miss Cannon at the Harvard Observatory, and by F. E. Seagrave at his private observatory in Providence. The work was prepared for publication by Wendell under Pickering's direction. The observations were made during the years 1889 to 1899, and the results published with appropriate detail.[15]

A similar investigation was undertaken of 58 variable stars of long period in various parts of the sky visible at Cambridge. Many observers took part, especially Wendell, Reed, Seagrave, Waite, Campbell, and Miss Cannon.[16]

In further extension of the visual investigations of variable stars, Miss Cannon prepared a discussion of the maxima and minima of all known variables of long period from data derived from the published results of 38 observatories and scientific journals. The information contained in these publications was based on the labors of nearly 200 observers of different countries, and included observations made from 1596 to 1909. Although the investigation thus covered three centuries of variable star problems, the vast majority of the observations had been made within the last half century. Tables were prepared by Miss Cannon, giving the dates of maxima and minima and much other information for over 400 variables.[17]

During the years 1902 to 1905, considerable progress in the study of variable stars was made under Pickering's direction at Cambridge, by the systematic observation and discussion of 75 variables of long period. The methods used were similar to those already described. A few observations were contributed by amateur astronomers, but the greater part of them were made at the Observatory by Miss Cannon and Mr. Campbell. When the variables were too faint at minimum

[15] H. A., **37**, Part 1, 1900.
[16] H. A., **37**, Part 2, 1902.
[17] H. A., **55**, Part 2, 1909.

to be observed with a small telescope, observations were made by Wendell with the 15-inch refractor, or by Campbell with the 24-inch reflector.[18] A large extension to the number of sequences of comparison stars was also made at about the same time.[19]

Visual observation of variable stars has been carried on until the present time, and has been greatly aided by the contributions of other observatories and astronomers. The results for the years 1906 to 1910, with a few unpublished observations of preceding years, were discussed and prepared for publication by Campbell, who himself made about half of the 23,000 observations. The remaining observations were made by 17 other members of the Observatory, and by 21 professional and amateur astronomers in other places. The number of observations of variable stars published at Harvard was thus increased to over 40,000. In the later work, the estimates of magnitude of the variables were made directly from the known magnitudes of the comparison stars, instead of in grades, thus decreasing the work of reduction without loss of accuracy. From 1906 to 1910, 328 variable stars were observed, and 279 additional sequences of comparison stars were selected and measured.[20]

Similar investigations were continued under Campbell's supervision during the years 1911 to 1916. The contributions of amateur astronomers became of increasing importance during this period through the enthusiastic cooperation of the members of the American Association of Variable Star Observers, to whom reference is made elsewhere. Assistance was also given by the Variable Star Section of the British Astronomical Association, the South African Association for the Advancement of Science, and by Dr. Mitchell, Director of the Leander McCormick Observatory. The published results contain observations of 323 variable stars of long period

[18] H. A., 57, Part 1, 1907.
[19] H. A., 57, Part 2, 1908.
[20] H. A., 63, Part 1, 1912; Part 2, 1913.

during the years 1911 to 1916; and the maxima and minima of 272 variables during the years 1900 to 1920. The observations of the members of the A. A. V. S. O. for 1911 were published by the Observatory, but since that time they have appeared in Popular Astronomy.[21] Extensions of the same investigations, the discussion and publication of which are in progress, have been carried on until the present time. Similar observations are planned for the future, until sufficient data shall be accumulated to make possible a definitive study of the behavior of long period variables.

Photographic Methods for Variable Stars.—Of more than 4000 variable stars discovered at the Harvard Observatory, very few have been found visually. That method is slow and difficult. Photographically, the case is very different. A series of photographic charts of any region is easily made on dates sufficiently separated. A comparison of these plates can then be made under proper illumination in a comfortable room, and the presence of any star of varying intensity may be detected. Even easier methods have been developed. Early in the work of the Henry Draper Memorial, plates made with the telescope and objective prism were obtained which showed hundreds of spectra, nearly all of which contained dark lines. It was soon found by Pickering and Mrs. Fleming that special objects having bright hydrogen lines of Class Md, usually long period variables, could be picked up readily by a rapid inspection of the plates.[21a]

Various other methods were derived for the detection of variables, such as an automatic series of chart exposures on the same plate, causing each star to appear as a succession of black dots. In this way a Cepheid variable of short period

[21] H. A., 79, Part 1, 1918; Part 2, 1926.

[21a] In 1922, the notation Md was dropped by action of the Committee on Spectral Classification of the International Astronomical Union and a decimal classification was adopted instead of small letters for subdivisions of M stars. Trans. Int. Ast. Union, 1, 97, 1922.)

will often show distinct changes in the intensities of the images. Another and more effective method is the superposition of a positive of one date on a negative of another date. The superposed light and dark images of an invariable star tend to neutralize each other, while the images of variable stars show a very different effect. Stereocomparators have also been effectively employed. By these methods, in general, the great additions have been made to the lists of variable stars in globular clusters, the Magellanic Clouds, and the Milky Way, as well as elsewhere in the sky.

After more than 3000 variables had been found at the Observatory by various methods, in areas selected without a systematic plan, a Durchmusterung of variable stars for the whole sky was suggested in 1906. It was proposed to make the effort international and to let it extend to as faint stars as possible. Not meeting with much response from other institutions, the Harvard Observatory undertook to carry out the plan by the use of the Harvard Map of the Sky, which shows stars to the tenth or eleventh magnitudes.[22] The method used was the superposition of a positive on a negative, using five plates made on different dates. The observations were made chiefly by Miss Cannon, Miss Leavitt and Miss Leland. It is evident that the greater the number of plates of a region examined (up to a certain limit) the more variables will be found.

Through systematic investigation many new variables have been found in different parts of the sky, and the results when completed will enable a definitive study to be made of the distribution of variable stars. While the total number of variables which exists in a given area is not detected by an examination of five plates, Pickering showed that the approximate total number can be derived from a study of the number of variables already known and the rate of increase as the number of plates examined becomes greater. For example, Region 3 of the Harvard Map probably contains 42 variables sufficiently bright to appear on the plates, of which 18 were

[22] H. C. 71, 1903.

previously known, 8 were added by the examination of five plates, and about 16 remain to be detected.[23]

The rapidly increasing collection of celestial photographs early called attention to the possibility of a photographic study of variable stars. The discovery of over 200 new variables by means of their spectral peculiarities emphasized the problem. The first need was for sequences of comparison stars, which were accordingly selected by Mrs. Fleming for 222 variables. The determination of the photographic magnitudes presented insuperable difficulties at that time; photographic magnitudes on an absolute scale, later developed by King, were not known. The magnitudes that were used were reduced by means of visual magnitudes and were provisional in nature, but gave empirical determinations of the relative brightness of the stars. The magnitudes of 707 variables were derived on all available plates; the observations, over 20,000 in number, extended over the years 1885 to 1905, and were made by Mrs. Fleming and Misses Breslin and Leland. Aid was also given by Misses Gill, Wells, and Stevens.[24]

Variable Stars in Globular Clusters.—The discovery that many variable stars are present in certain globular clusters was made by Bailey, at Arequipa, in 1895. Before that time a few stars in or near such clusters had been announced as variable, but little attention had been paid to them. While comparing plates of the fine globular cluster ω Centauri made on different dates, Bailey noted that several of the stars were variable. This led him to undertake a systematic search in various globular clusters on plates made by him with the 13-inch refractor of 16 feet focal length. Fortunately, Messier 3 and Messier 5 were among the first clusters examined, and both yielded surprising results. Of the stars visible to the naked eye in the whole sky, not more than one or two per cent are known to be variable. In the cluster Messier 3, an examination

[23] H. C. 116, 1906; 127, 129, 130, 133–135, 1907; 137, 140, 142, 1908; 151, 1909; 152, 159, 162, 1910; 165, 1911; 179, 1913; 218, 1919.

[24] H. A., 47, Part 1, 1907; Part 2, 1912.

of 900 stars revealed 132 variables, about 1 in 7, or 15 per c of the stars examined. Approximately the same ratio ' maintained in this cluster, when, later, Shapley at Mo Wilson increased the number of stars examined to 1000, the number of variables to 150.

Only a few clusters have large numbers of variables. many clusters the percentage of variables is less than among lucid stars. For example, in the fine cluster N. G. C. 6 out of 600 stars examined only one variable was found, or sixth of one per cent. Altogether, at that time, 509 varia stars were found by an examination of 19,000 stars in 23 clust something less than three per cent. The total number of knc variables in clusters has since that time been much increa by the observations of Misses Leavitt and Woods at the Harv Observatory, by Shapley and his assistants at Mount Wil and by others. Several hundred new variables have thus b added, but it does not seem probable that the number will greatly increased in the future, since the number of globı clusters, at least within our present grasp, is limited, and nea all the important ones have already been examined.

The number of stars in some of the globular clusters is v great. Photographs made at the Mount Wilson Observat indicate the presence of at least 50,000 stars in Messier faint globular cluster which to the naked eye appears a hazy star of about the sixth magnitude. From theoret and other considerations it appears probable that great nı bers of very faint stars are present, and that the whole num may be half a million or more. At first it was thought that w a sufficiently powerful equipment large numbers of varial might be found among the faint stars of these clusters. T far, however, though carefully sought, no variable stars h been found among the fainter stars in clusters. Variabi evidently marks a certain epoch in a star's development occurs only there.

The name "cluster variables," suggested many years by the writer, is generally applied to these variables. T

PLATE XVI.—THE GLOBULAR CLUSTER ω CENTAURI.

(*Facing page 182*)

form a subdivision of the Cepheid group, belonging to Pickering's Class IV, the short period variables. The periods of cluster variables are between a fourth and three fourths of a day, but the great majority have periods of about half a day, or a little more. The median magnitude, however, of all variables of this type in any cluster is uniform, whatever the length of the period. This was noted early, and later confirmed by Shapley. The range of variation in brightness is in general from half a magnitude to a magnitude and a quarter. The light changes are continuous, the increase to maximum extremely rapid, the duration of maximum very brief, the decrease relatively slow, with a continued slow decrease during the minimum period. A detailed study by the writer of the variables in ω Centauri was the first published.[25] Studies of the clusters Messier 3, 5, and 15 followed it.[26] These articles contain the measurements and elements of the variables, and the light curves; they are illustrated with marked photographic charts of all the variables. From an examination of the globular cluster, N. G. C. 3201, Miss Woods found 56 variables, and from a similar examination of N. G. C. 6362, 15 variables.[27]

A provisional catalogue of globular clusters was prepared by Bailey in 1916; he concluded that 76 such clusters were known at that time. A study of the distribution of the stars in ten clusters was also given.[28] The number of known globular clusters was later increased by Shapley, who has classified 95 such clusters, and in collaboration with Miss Sawyer, has determined their photographic magnitudes.[29]

The remarkable extension of our knowledge of the structure and dimensions of the galactic system and the universe beyond, which has resulted from Shapley's studies of the Cepheid variables in clusters and elsewhere, will be referred to in Chapter XV.

[25] H. A., **38**, 1902.

[26] H. A., **78**, Part 1, 1913; Part 2, 1917; Part 3, 1919.

[27] H. C. 216, 217, 1919. See also H. C. 266 for an account of N. G. C. 6723.

[28] H. A., **76**, No. 4, 1916.

[29] H. B. 848, 849, 1927.

The Magellanic Clouds.—As already stated, a persistent search for variable stars was undertaken by different members of the Observatory, as soon as the number of photographs of the stars was sufficient for the purpose. The method most employed was the superposition of a positive on several negatives made on different dates. This search was most intensive in certain selected areas, and the results obtained in different regions varied greatly. The nebulous area in Orion, where variables had been known or suspected for many years, was examined by Miss Leavitt, who found 79 variables, many of them new. An examination was also made of the nebulous regions in Scorpio, Sagittarius, and Carina, the Trifid Nebula, and other special regions, which altogether revealed several hundred variables. It was not until 1905, however, when a series of Bruce plates of the Magellanic Clouds, having long exposures and showing very faint stars, was received from Arequipa, that Miss Leavitt made the important discovery that the Clouds contained variable stars in great numbers. By 1908, the number known in the two clouds had reached 1777.[30] In publishing the positions of the variables, rectangular coordinates were given in preference to right ascensions and declinations, because the labor involved in their preparation is less, and because their utility for identification is greater. For the safe identification of closely massed stars, however, a marked photograph is the best aid. Miss Leavitt gave the periods of 16 variables in the Small Cloud, using a provisional scale of magnitudes. With the adoption of a standard scale of magnitudes for the stars of the North Polar Sequence, and with the methods employed for its extension to all parts of the sky, the subject was again taken up, and improved light curves and periods were obtained for 25 variables in the Small Magellanic Cloud. The periods of these 25 stars are from $1^d.3$ to $127^d.0$, but 22 of them are less than 17 days. The variables are of the Cepheid type in nearly all cases. The light curves resemble those of the cluster variables.

[30] H. A., 60, No. 4, 1908; H. C. 78, 79, 82, 90, 91, 1904; 96, 1905.

The Period-luminosity Curve.—Probably the most important result of the investigation of the Magellanic Clouds was the discovery of the so-called "period-luminosity law," which Miss Leavitt found to hold for the 25 variables which she discussed, with only moderate irregularities. By plotting the periods as abscissae, and the measured magnitudes as ordinates, and drawing a smooth curve through the observations, a relation between the two quantities is clearly shown: the fainter the star the shorter the period. When the abscissae were represented by the logarithms of the periods, the resulting curve was sensibly a straight line. Since the variables are evidently all members of the Cloud, and hence all at approximately the same distance, what is true for the apparent magnitudes must be true for the absolute magnitudes, and the law—if it is a law—thus established becomes of great importance, and capable of wide extension. Shapley has shown, however, that in the case of the Small Cloud, the depth, or diameter of the cloud in the line of sight, is sufficient to produce a dispersion in magnitude of $0^m.14$. The number of variables included in Miss Leavitt's discussion was unfortunately rather small, but the data have been much increased since that time, especially by the studies of Shapley, whose work on the Magellanic Clouds, and the application of the period-luminosity curve to the determination of celestial distances, will be referred to later.[31]

The Novae.—Novae form the first group in Pickering's classification of variable stars. The term "temporary star" is preferred by some writers to "nova," as undoubtedly more exact. The word "nova," however, is older, briefer, and more convenient, and, with suitable interpretation, may well be retained. The sudden enormous increase of light, while in no sense a creation, must mark some catastrophic event in the life history of the star. Usually but one such outburst is known for a particular nova.

[31] H. C. 173, 1912.

Considerable attention has been paid to new stars at the Harvard Observatory. The first Harvard Circular, issued on October 30, 1895, contained the announcement of a nova in Carina, discovered by Mrs. Fleming from its characteristic spectrum shown on a plate made in the preceding April. A later plate revealed a marked change in the spectrum. An examination was then made of all available chart plates of the region, from which it was shown that the star had been invisible, up to March 5, on plates showing stars as faint as the fourteenth magnitude. On April 8 it was of the eighth magnitude, and on July 1 of the eleventh magnitude.[32] A similar examination was made in many other cases. At that time only 12 well-authenticated novae were known, and today the number is only about 70, if those in spiral nebulae are excluded. When a nova was announced, not only were old plates examined but new chart and spectrum plates were made and repeated as long as the object remained accessible.

Observations of Anderson's new star of 1901, Nova Persei, No. 2, were made from February 22 onward, and an especially good record was obtained of the striking spectral changes which occur at or near maximum. In this case the nova rose nearly to the magnitude zero.[33] An elaborate study of the light changes was made by Campbell,[34] and later a similar study of the light curves of Nova Geminorum, No. 2,[35] and Nova Aquila, No. 3. Miss Cannon made a very complete study of the spectral characteristics and changes for Nova Persei, No. 2, with detailed lists of the lines observable at different times.[36] No observable star occupied the position of Nova Persei, No. 2, previous to the outburst in 1901, but in other cases the nova had been present as a faint star. Such a star was Nova Aquilae No. 3. This object is shown on photographs of the region in the Harvard collection made in the 30 years from 1888 to

[32] H. C. 1, 1895.
[33] H. C. 56, 57, 59, 1901.
[34] H. A., 48, No. 2, 1903.
[35] H. A., 76, No. 11, 1915; 81, No. 2.
[36] H. A., 56, No. 3, 1912.

1918, during which time it was of about magnitude 10.5, with various fluctuations in brightness. In June, 1918, it rose

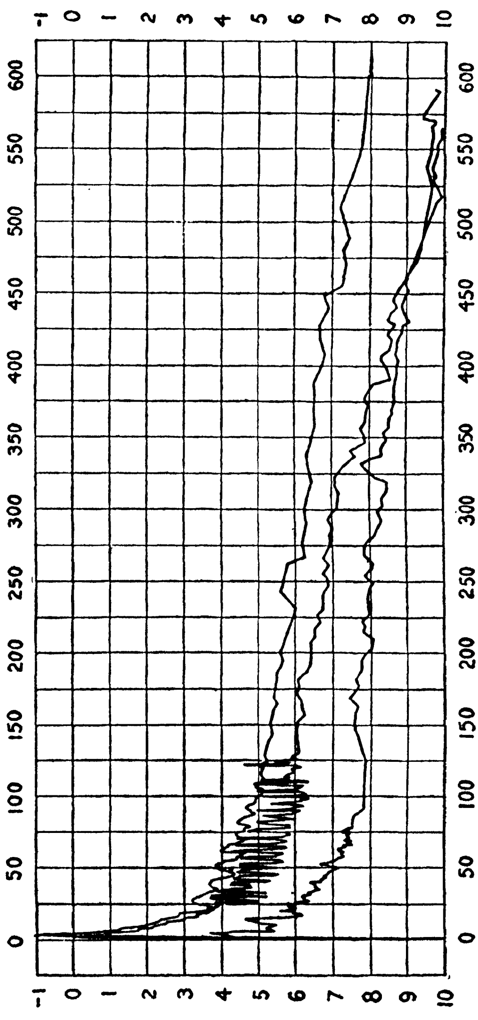

FIGURE II.
Light curves of novae. Comparison of Nova Aquilae, No. 3, Nova Persei No. 2, and Nova Geminorum No. 2.

to nearly the magnitude zero. Its early spectrum was approximately Class A, and its spectral changes were carefully followed

at the Observatory.[37] A very complete and interesting record was secured of Nova Geminorum, No. 2, discovered by Enebo on March 12, 1912, showing clearly the successive changes in the spectrum, from one having absorption lines similar to α Canis Minoris to the typical bright line spectrum of novae.[38] Davidovich made a study of the spectrum and luminosity of Nova Pictoris 1925.4, in which he determined the absolute magnitude. He reached the conclusion that the increase of light was probably produced by an expansion of the star, that is, by an increase in the size of the luminous surface rather than of its intensity.[39]

During the years 1919 to 1921, a systematic photographic search of the Milky Way, where practically all novae appear, was undertaken for the discovery of novae and especially for a study of their distribution and frequency. The observations were made chiefly by Misses Woods and Mackie, who, as a result of their search, discovered 8 novae, in addition to finding 6 novae which were already known. During this investigation 1049 pairs of plates were compared. Owing to the brief duration of maximum of a typical nova and to difficulties inherent in such observations, it is probable that such an examination would disclose all novae of the fifth magnitude, or brighter, at maximum, and a constantly decreasing proportion as the magnitude was fainter down to the ninth magnitude. None fainter than the ninth magnitude would be found. From the results actually obtained it appears probable that, on the average, one or possibly two novae of the sixth magnitude, or brighter, at maximum, appear in the sky yearly and perhaps ten, or possibly twice that number, of the ninth magnitude, or brighter. Probably no nova as bright as the third or fourth magnitude now escapes detection, but very few of the faint novae that occur are ever observed.[40]

[37] H. C. 208, 1918.
[38] H. C. 176, 1912.
[39] H. C. 295, 1926.
[40] Pop. Astr., 29, 554, 1921.

The Amateur's Contribution; the A. A. V. S. O.—The American Association of Variable Star Observers, although not a part of the Harvard Observatory nor officially under its supervision, has had, nevertheless, such intimate relationship with the Observatory, and has contributed so much to our knowledge of variable stars, that some reference here to its activities seems fitting. Work preparatory to such an association was in progress for many years; as early as 1882 Edward C. Pickering called attention to the opportunities for amateur observers of variable stars. A special section was given to variable stars in his Annual Report, beginning in 1905. Already several professional and amateur observers were sending their observations to the Harvard Observatory for discussion and publication. The number increased each year until the foundation of the A. A. V. S. O. in 1911. In the August number of Popular Astronomy for that year, the editor, Professor H. C. Wilson, suggested the formation of an astronomical society for the observation of variables, similar to the Variable Star Section of the British Astronomical Association. This plan was promptly approved by the volunteer observers already at work.

Mr. William Tyler Olcott, a well known writer of astronomical books and an assiduous observer, undertook its direction. His rare ability, enthusiasm, and good fellowship brought success to the undertaking. Popular Astronomy offered to publish the observations free of expense to the members. Indispensable aid was given by the Harvard Observatory in the way of photographic charts of the variables and directions for observation. Most important of all, Pickering inspired the members with his own enthusiasm. Various professional astronomers joined the Association, but by far the greater number were amateurs. Men of all ranks in life became members. Extremely active and helpful was Mr. David B. Pickering, a successful business man and an equally successful watcher of the stars. One of the most interesting members was Mr. C. Y. McAteer, an elderly locomotive engineer, who after long runs

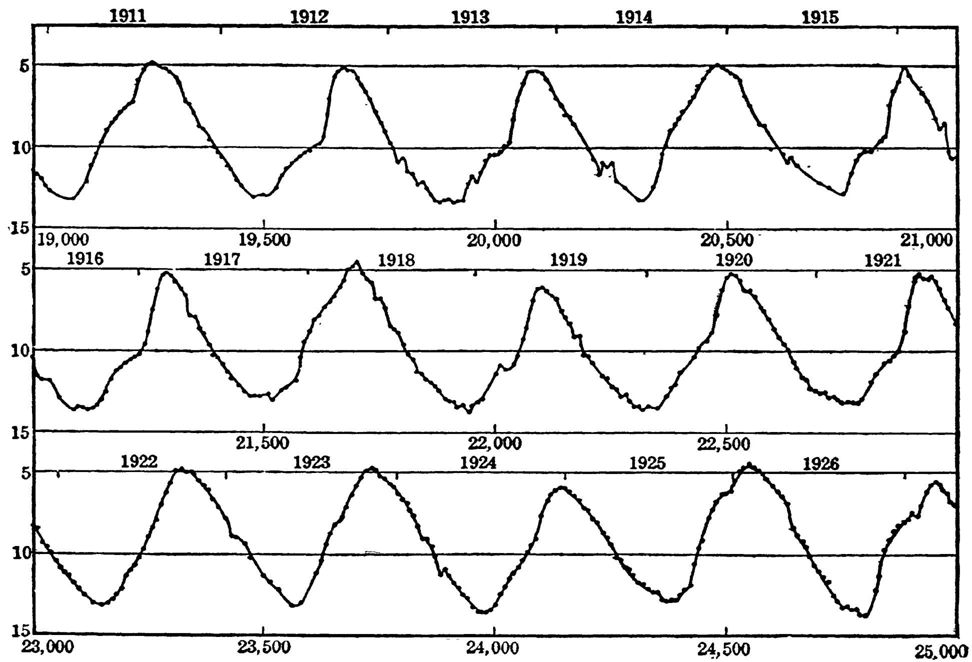

FIGURE III.

The light curve of the long period variable star χ Cygni, embodying the observations made between 1910 and 1927 by amateur astronomers, chiefly the American Association of Variable Star Observers, which has its headquarters at the Harvard Observatory. Years are indicated above the curves, and Julian days (which are reckoned continuously from January 1, 4713 B. C.) are shown below. The scale on the left margin is in visual stellar magnitudes.

on his railway train, was never too weary to observe the stars. For many years, Mr. Leon Campbell has been most efficient in maintaining the relations between the Association and the Observatory, and in increasing the number and quality of the observations. The headquarters of the Association have always been at the Observatory, where the annual reunions are held. The Association has a collection of over a thousand astronomical lantern slides for the use of members who wish to give illustrated talks on astronomy, it possesses a library of about a thousand volumes and pamphlets, and owns several telescopes, which are loaned to active observers who do not possess suitable equipment.

From a group of seven observers at the beginning in 1911, the Association has grown to seventy five observers in 1927. During the intervening years the members have made nearly 250,000 observations. About 500 variables have recently been under observation, and 20,000 dates of maximum and minimum have been derived. The observations have been published in Popular Astronomy, but some discussion of them has been made by Campbell at the Observatory, who used them to great advantage in his investigation, A Tentative Classification of Long Period Variables.[41] The Association has observers in Argentina, Australia, Canada, England, France, Germany, India, Italy, Japan, Russia, and South Africa, in addition to the United States. The members are so well distributed around the earth that observations can be maintained almost continuously.

[41] H. Repr. 21, 1920.

CHAPTER XIV

CLUSTERS AND NEBULAE

STAR clusters and nebulae are important and conspicuous features of the Milky Way star fields. Perhaps on account of their frequent proximity they were long classed together, and the two names are even now rather loosely used to describe them; for many so-called "nebulae" are really clusters of stars, and clusters are occasionally involved in nebulosity. The subdivisions, however, will be useful for general purposes, and are retained in the discussion of researches that have been carried on at the Harvard Observatory.

Stellar Clusters.—Attempts to represent dense star clusters by drawings, before the introduction of photography, were made by Trouvelot. Two such drawings of the globular clusters N. G. C. 6205 and 6341, in Hercules, are shown among the illustrations in the Annals.[1] Clusters can be well and accurately represented only by photographic plates made with a telescope of rather large size. In 1888 the Observatory acquired a suitable instrument which, after some trials at Cambridge, was set up on Mount Wilson in 1889. It was an achromatic refractor of 13 inches aperture with a focal length of 16 feet. It could be used either visually or photographically and gave excellent definition in either case. On Mount Wilson many photographs of clusters were made by King and Black; later the telescope was in use at Arequipa, where the investigation was continued on a larger scale.

An early attempt to gain some information in regard to the distribution of stars in the globular cluster ω Centauri was made by Mr. and Mrs. Bailey at Arequipa, in 1893. A reticle composed of 400 squares, each 90″ on a side, was placed

[1] H. A., **8**, Part 2, 1876.

over the image of the cluster and the number of stars was counted in each square. The number of stars photographed[2] in one fourth of a square degree, with an exposure of two hours, was 6389.

The distribution of the stars in several clusters was later investigated by Pickering and Mrs. Fleming, who also made some observations of positions, brightness, and class of spectrum. In general, the positions were given in rectangular coordinates, expressed to tenths of a second of arc.[3]

A catalogue of 263 bright clusters and nebulae was compiled by Bailey in 1908, constituting a uniform Durchmusterung of such objects for the whole sky. Photographs of one hour exposure made with Cooke lenses of one inch aperture and showing stars to the eleventh magnitude were examined; all clusters and nebulae visible on such plates were included in the catalogue, and no others. The descriptions of the objects were made in general from an examination of Bruce plates of one hour exposure.[4] Various typical examples are illustrated, all on the scale, $1' = 1$ mm. A somewhat similar study was made of the globular clusters, but all clusters believed to be globular, 76 in number, were included.[5] The number of globular clusters has since been considerably extended, especially by the later investigations of Shapley,[6] who in 1922 gave the whole number known as 95. Many of the later additions do not appear globular on photographs of moderate exposure, but they reveal the typical feature of a globular cluster—a dense population of faint stars—on plates made with large instruments and long exposures. Shapley and Miss Sawyer have divided the globular clusters into twelve subclasses, based on the degree of apparent concentration of the stars to the center, and probably giving an indication of the stage of development.[7]

[2] Astr. and Ap., **12**, 689, 1893.
[3] H. A., **26**, Part 2, 1897.
[4] H. A., **60**, No. 8, 1908.
[5] H. A., **76**, No. 4, 1916.
[6] H. B. 775, 776, 1922; 849, 1927.
[7] H. B. 849, 1927.

In the course of the researches which he describes in the second Monograph of this series, Shapley has shown that the globular clusters have a certain uniformity, so that their distances and distribution may be studied by means of their integrated apparent brightness, the brightness of individual stars, and their apparent diameters. In conjunction with Miss Sawyer he has obtained the necessary data on the integrated apparent magnitudes,[8] and on the apparent diameters.[9] The ellipticities of all known globular clusters, as well as the class and orientation to the galactic plane[9] have also been examined by Dr. Shapley and Miss Sawyer. A consideration of these data, which concern the history and internal economy of a cluster, rather than its distance, is contained in Harvard Monograph No. 2.

Investigations of Nebulae.—After the installation of the "Great Telescope" in 1847, the Bonds promptly began investigations on the great nebula in Orion and that in Andromeda. Early in 1848, G. P. Bond presented a paper to the American Academy, "An Account of the Nebula in Andromeda," in which he gave an historical account of previous investigations by other astronomers, and the results of his own observations with the new 15-inch telescope. Although he saw many stars in the region, Mr. Bond did not, of course, resolve the nebula itself.[10] Later in the same year, the director, W. C. Bond, published a paper entitled, "Description of the Nebula about the Star θ Orionis." Bond was inclined to believe then that the Orion Nebula was resolved into stars by the 15-inch telescope under the best conditions. At that time, indeed, a belief prevailed that all nebulae might be resolved with a sufficiently powerful telescope. He made a list of stars, the positions of which were given in rectangular coordinates.[11] In each of the above communications, a careful drawing was given of the appearance of the nebula.

[8] H. B. 848, 1927.
[9] H. B. 852, 1927.
[10] Mem. Amer. Acad., 3, 67, 1848.
[11] *Ibid.*, p. 87, 1848.

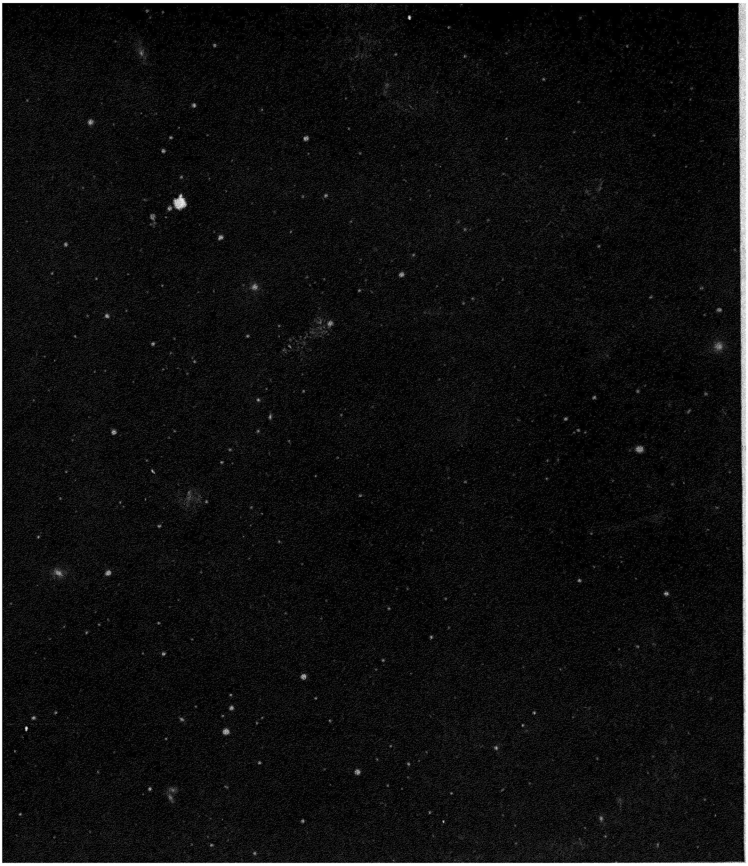

PLATE XVII.—EXTRA-GALACTIC NEBULAE BELONGING TO THE COMA-VIRGO GROUP. (Photographed with the Bruce Telescope.)

(*Facing page 194*)

Plate XVIII.—Star Field in Cygnus, Showing the North America Nebula and the Filamentary Nebula.

Later the study of the Orion Nebula was again undertaken by G. P. Bond. Aside from the intrinsic interest of the nebula itself, certain adverse criticisms of the results of W. C. Bond's earlier investigation led his son to devote himself for many years to an elaborate study of this object. He began his observations in 1857, and continued them with some interruptions caused by his studies of the Great Comet of 1858, and by his father's death in 1859, until his death in 1865, when the investigation was nearly complete. It was promptly finished and prepared for publication by Safford. The most elaborate care was taken in the preparation of the drawing of the nebula. The positions of a thousand stars seen in the region were given, expressed in right ascensions and declinations, and the recognized faint nebulosity was considerably extended. Bond spared no labor in making his work as accurate as possible and it may be safely said that the results were all that could be attained visually with a telescope of that size. Photographs, however, were destined soon to replace drawings in the representation of such objects.[12]

An early photographic study of the Orion Nebula was made by W. H. Pickering on photographs taken with various telescopes during the years 1886 to 1890. Mr. Pickering made a revision of the positions of the Bond stars in the region, 38 of which were not seen on the photographs in the given positions. In a few cases this was caused by the obscuration of the image of a faint star by the large image of an adjacent bright star, but 20 of the Bond stars do not appear on the plates. On the other hand, 146 additional stars not given by Bond were found in the region. A study was made of the intrinsic brilliancy of different parts of the nebula, and of the isophotal contours. One of the most interesting results was the discovery of the great nebulous cloud in which the whole region is enveloped.[13]

During the years 1866 to 1870, precise positions were determined for several hundred nebulae with a large filar micrometer

[12] H. A., **5**, 1867.
[13] H. A., **32**, Chap. 2, 1895.

attached to the 15-inch telescope. The list of nebulae was selected for the most part from the General Catalogue of Herschel. The nebulae were fully described, and for the brighter objects spectroscopic observations were made. Several observers took part in this investigation, especially Winlock, Peirce, G. M. Searle, and Austin.[14] Another series of observations of nebulae was made with the same telescope during the years 1879 to 1882, by Pickering, Searle, Upton, and Wendell. The diameters were determined by means of a double-image micrometer, the brightness with a photometer, and the spectra by a direct-vision prism.[15]

G. P. Bond, Coolidge, Tuttle, and Safford discovered 28 new nebulae in connection with their observation of the Bond Zones during the years 1848 to 1863. Under the directorship of Winlock, 13 more nebulae were found, and Pickering added several new gaseous nebulae, which he discovered by means of a direct-vision prism placed in front of the eyepiece of the 15-inch telescope. The discovery of nebulae received an enormous impetus by the introduction of photography into astronomical research. In the early eighties, photographic methods were beginning to replace visual observations in many lines of investigation, and nowhere to greater advantage than for nebulae. For such work the advantages of a photographic doublet were early pointed out by Pickering; in the case of faint, luminous surfaces, the wide angle and the short focus permit very faint objects to be shown over an area much larger, for a single plate, than is possible with other forms of refracting telescopes. As a test of this method, Mrs. Fleming made an examination of five plates, of exposures from one to two hours, made with the Bache 8-inch doublet in 1888; the number of known nebulae in the region was nearly doubled.[16]

A list of all nebulae discovered at Harvard was begun in 1908. Consecutive numbers were given, from the first nebula

[14] H. A., 13, Chap. 3, 1882.
[15] H. A., 33, No. 7, 1900.
[16] H. A., 18, No. 6, 1890.

found by G. P. Bond in 1848. From 1848 to 1883, by visual methods, 55 new nebulae were discovered, and by 1907, chiefly by their spectral peculiarities as shown on photographic plates, the number was increased to 108. However, with the beginning of long exposures with the Bruce photographic 24-inch doublet at Arequipa, the possibility of a very great increase in the number of faint nebulae became apparent. A survey of the whole sky was planned for the discovery of nebulae and other objects, using Bruce plates of four hours exposure. The far southern regions were photographed with such exposures, but the remainder of the sky has not been systematically covered. By an examination of the plates made from 1898 to 1901, Stewart increased the Harvard list of nebulae to 785; and Frost later extended it to 1238, from plates made from 1903 to 1904. From an examination of Bruce photographs having exposures of 2^h to 4^h, made from 1901 to 1908, Bailey and Miss Waterbury carried the number forward to 2897.[17] The number has recently been increased greatly by the investigations carried on under Dr. Shapley.[18] Systematic nebular studies have been maintained and nearly 10,000 new nebulae, as yet unpublished, have been found on Harvard plates and are being measured for magnitude, position, and dimensions. Probably many thousands of additional nebulae will appear on the photographs for the Harvard collection which are now being made at the new Boyden Station in South Africa.

Numerous objects which have been classified as nebulae, such as many of the spiral nebulae, are now known to be distinct systems, largely stellar. The Milky Way or galactic system, with its complicated structure of star clouds, clusters, bright and dark nebulae, and scattered stars, is not the only stellar system. Its nature, and that of some other systems of stars and nebulae will be given some consideration in the next chapter.

[17] H. A., **60**, No. 6, 1908; **72**, No. 2, 1913.

[18] H. B. 773, 777, 780, 1922; 784, 1923; 808, 1924; 816, 1925; H. A., **85**, No. 6, 1924.

CHAPTER XV

STRUCTURE AND DIMENSIONS OF STELLAR SYSTEMS

THE structure, dimensions, and distances of the different systems which make up the visible universe have long engaged the attention of astronomers, mathematicians, and philosophers. In this chapter the attempt is made to give a brief outline only of the main contributions to this subject which have been made by members of the Harvard Observatory.

The correct interpretation of the revelations made by the telescope and spectroscope is often difficult. It may now be stated with confidence, however, that the visible universe of stars, clusters, and nebulae is not a single system, but consists of many systems resembling each other in greater or less degree, widely separated, and relatively independent. It is natural that our first and chief interest should be directed toward the galactic system, which contains our sun as one of its units.

Peirce's Survey of the Galactic System.—The first attempt at the Harvard Observatory to determine the form of the Milky Way, or the galactic system, was made by Charles S. Peirce. In connection with his photometric work undertaken during the administration of Joseph Winlock, in the years 1871 to 1875, Peirce made a study called "Form of the Galactic Cluster." He states that "The chief end of observations of the magnitudes of the stars is to determine the form of the cluster in which our sun is situated," meaning the galactic cluster. Without attempting numerical accuracy, he endeavored to show the general form of the surfaces of equal star-density throughout the cluster.

Peirce first discussed the subject on the assumption that the proportion of stars of different absolute magnitudes is the same throughout space; and afterwards, how far the conclusions thus derived are affected by the assumption of the greatest variety in the magnitudes. He divided the whole sky into 32 equal regions, consisting of the north and south polar regions, a central Milky Way zone, and four intermediate zones parallel to the galactic equator. Each zone was divided into six equal parts. A discussion was then made of the number of stars from the first to the sixth magnitude in each region, using Behrmann's and Heis' maps. His results appeared to indicate that the intermediate regions adjoining the polar regions had no more stars than the polar regions, and that the intermediate regions adjoining the galactic central zone had about the same number of stars as the galactic zone. This he explained on the hypothesis that between the zones adjacent to the galaxy and those adjacent to the polar regions, the line of sight is nearly tangential to the surfaces of equal condensation.

Peirce also found that for stars from the first to the sixth magnitudes the mean distances as calculated from the proper motions of Mädler were nearly as the square roots of the distances deduced photometrically.

The investigation was of a pioneer nature, founded on scant data. No reference was made to the clustering tendency of the stars in the Milky Way, nor to the presence of obscuring clouds, at that time probably unsuspected.[1]

Pickering's Studies of the Milky Way.—Considerable work bearing on the structure of the Milky Way was done by Pickering during his long directorship. Discussions regarding the distribution of stars of different spectral types have already been referred to under the subject of Spectroscopy. In connection with his photometric catalogues, Pickering discussed the distribution of stars of different magnitudes. Dividing the stars into groups half a magnitude apart, he studied the

[1] H. A., 9, Chap. 5, 1878.

distribution of the 4193 stars of the early Harvard Photometry, together with that of the 324,000 stars of the Northern Durchmusterung, and the 7363 stars of the Uranometria Argentina. Pickering found the actual number of stars observed was less than that indicated by theoretical considerations, on the improbable but convenient assumptions that the stars are of equal brightness and uniformly distributed in space.[2]

Pickering's discussion was carried forward later with increased data. The density of the Milky Way was determined from counts of the stars of different magnitudes. Good determinations of magnitude had been made of all stars in the sky to magnitude 7.0 or 7.5. For fainter stars the revised magnitudes of the Northern Durchmusterung were also used to about the tenth magnitude, and were fairly reliable. A few still fainter stars were provisionally employed. The proportion of galactic stars to nongalactic stars was found to be about two to one for stars to magnitude 7.5, the ratio increasing somewhat for fainter stars. The number N of stars of each magnitude in the sky was also given, which followed closely the formula, $\log N = 0.51M + A$, the coefficient of M decreasing, however, for fainter magnitudes. The really faint stars, which form the galactic clouds, were beyond the reach of this discussion.[3]

Miscellaneous Investigations of the Milky Way.—Minor contributions to the structure of the Milky Way were made by Bailey, who prepared a photographic map of the southern Milky Way in nine charts, each covering an area of about 30° by 40°. The photographs were obtained with a Cooke lens of 1.5 inches aperture and 13 inches focal length. Each plate was adjusted so that the longer axis was perpendicular to the central line of the Milky Way. The original photographs were made at Hanover, South Africa. Mr. L. G. Schultz assisted in the photographic work. The exposures were on the average about 12 hours.[4]

[2] H. A., **14**, Chap. 14, 1884.
[3] H. A., **48**, No. 5, 1903.
[4] H. A., **72**, No. 3, 1913.

A similar task was carried out by Bailey at Norwell, Massachusetts, for the Northern Milky Way. Because of the amount of artificial illumination, long exposures could not be made at Cambridge. Nine charts again show the northern regions, with some overlapping. Altogether, the 18 charts show the whole Milky Way, presenting clearly the familiar cloud forms and the dark obscured areas.[5]

To compare the density of the stars in the richest parts of the Milky Way with that at the galactic poles, a count was made by Bailey at Arequipa of the number of stars obtained on Bruce plates, with exposures ranging from 1^s to 6^h. Exposures of 1^s showed stars to magnitude 10.1, and exposures of 6^h, to magnitude 19.2. For the Milky Way region, one square degree was chosen in Sagittarius. The ratio of the number of stars in this area to the number at the south galactic pole varied from 2, for stars brighter than magnitude 9.5, to 160 for stars at the sixteenth magnitude. The presence of vast obscuring clouds in the Milky Way was pointed out.[6]

William H. Pickering made an attempt, in 1917 and 1918, to find the distance of the Orion Nebula and the Pleiades, by the use of the known relations between absolute magnitude and spectral type. The results obtained, however, are not in very good agreement with other and later determinations.[7]

Shapley's Measurement of the Galaxy.—When Dr. Harlow Shapley became director of the Harvard Observatory in 1921, he had already spent several years in systematic research looking toward the solution of the various problems concerned in the structure and size of the visible universe. The investigations naturally centered about the galactic system, whose size was soon found to be vastly larger than had been formerly believed by astronomers. It was apparent that the ordinary means of finding parallaxes must fail, when the depths of the Galaxy were to be sounded. Neither trigonomet-

[5] H. A., 80, No. 4, 1916.
[6] H. C. 242, 1922.
[7] H. C. 205, 1917; 206, 1918.

ric methods based on the earth's orbit or on the sun's path, nor spectroscopic parallaxes, would suffice for the study of the more distant stars. In photometric methods Shapley found the most hopeful outlook. However vast the distance of a star, the apparent magnitude compared with the absolute magnitude will yield the distance by a simple computation. The apparent magnitude can be found readily by visual or photographic photometry. To find the absolute magnitude is more difficult. By known methods of analysis the absolute magnitudes and distances of eclipsing binary stars can be found, but their number is small. Shapley placed his chief reliance on a study of the Cepheid variables, which thus became of the highest importance in his investigations. Fortunately, many Cepheid variables were already known, in the Galaxy itself, in the globular clusters, and in the Magellanic Clouds.

Miss Leavitt had shown in 1912 that for 25 Cepheid variables in the Small Magellanic Cloud the length of the period had a close relation to the apparent magnitude;[8] and, since all the stars in this Cloud are evidently at about the same distance, the relation holds true for absolute magnitudes. By extended investigations, Shapley showed that this period-luminosity relation, or curve, was true not only in the Small Magellanic Cloud, but was of universal application. The possibility was at once presented of finding the distance, however vast, of any cluster or aggregation of stars, provided Cepheid variables could be found among its units. From the period-luminosity curve the absolute magnitude could be directly read for any variable whose period had been found; and the distance, expressed in light years, could be derived by the formula

$$\log d = 1.514 - 0.2\,(M - m).$$

In a long series of papers,[9] Shapley gave his results on the determination of the distances from the sun of many celestial objects. At first he gave special attention to the globular

[8] H. A., 60, No. 4, 1908; H. C. 173, 1912.

[9] Mt. W. Contr. 115–117, 126, 129, 133, 151–157, 160, 161, 175, 176, 190, 1915–1920; Mt. W. Comm. 18, 19, 34, 37, 39, 44, 45, 47, 54, 62, 63, 64, 69, 1915–1920.

clusters, their distances, their relations to and distances from the galactic plane, as well as their form, size, and constituent units. Certain globular clusters contain many Cepheid variables, others none, as shown chiefly by Bailey's studies of Harvard plates. Shapley found, however, that the derivation of parallaxes could be made independently of the variables by substituting the magnitudes of the brightest stars in the cluster as the criteria of distance. The difference between the median magnitude of the variables in a cluster and the mean magnitude of the twenty five brightest stars proved for practical purposes to be nearly constant. For seven well-known globular clusters, the median magnitude of the brightest stars near the centers was 1.28 magnitudes brighter than the median magnitude of the cluster type Cepheid variables, with only small individual deviations. The investigation was thus extended to the globular clusters which contained no recognized variables.

The parallaxes having been determined, it is easy to obtain the dimensions of the clusters. Their average diameter is given as about 150 light years. They are enormous stellar systems composed of many thousands of stars, vastly more condensed near the centers than are the stars in the vicinity of our sun. In most cases, as shown at Harvard and Mount Wilson, the form is not strictly globular, but somewhat flattened, an oblate spheroid, indicating a revolution about the shorter axis. Such a system placed with its center in the position of our sun would extend in all directions a distance of some 75 light years, and would envelop hundreds of our nearest stars. The distances of the globular clusters from the sun are from about 15,000 to about 200,000 light years. They form an immense spheroidal or ellipsoidal group whose central plane appears to coincide with that of the galactic system. The center of both systems is probably in the direction of Sagittarius at a distance of some 40,000 light years or more, a conclusion differing widely from the view formerly held by astronomers that the sun is near the center of the Galaxy.[10] Notwithstanding

[10] Sci. Amer. Mon., p. 341, October, 1921.

their immense size and wide distribution, the globular clusters appear to have such an intimate relation to the galactic system that they may be regarded as roughly indicating its dimensions and outlining its form.

Since he became Director of the Harvard Observatory, Dr. Shapley has continued to give especial attention to the above and related problems. A summary of his recent work and present plans can best be given in his own words:

Ever since the study of the space distribution of globular clusters indicated the eccentric position of the solar system in the Galaxy, I have desired to investigate in detail those distant regions in the southern Milky Way where the center of the galactic system appears to be. The usual statistical methods of elucidating galactic structure from rather indiscriminate counts of stars and from measures of motions in the solar neighborhood seem to be too limited—wholly inadequate, in fact, for analysis of regions some twenty to a hundred thousand light years distant. The so-called Kapteyn universe, for instance, is deduced without regard to local clustering, and it combines the data from all galactic longitudes; many earlier attempts to outline the system did not even allow for differences in galactic latitude. The Milky Way system is obviously a conglomerate of single stars, groups of stars, clusters and great star clouds, seriously obscured in certain regions by nebulosity. A direct attack on the problem of the distances of the individual stars in the Milky Way, of the individual nebulae, and of stellar groups, by methods that reach far and give unambiguous results, appears to be the most satisfactory way of working out the details of galactic dimensions and structure, and in particular of determining the nature of the central regions of the galactic system . . .

As a preliminary, it should be recalled that all the known globular clusters, about a hundred in number, form a unified considerably flattened system of still higher order, symmetrical with respect to the galactic plane. Their distances range from fifteen thousand to about two hundred thousand light years, and the greatest diameter of the system, in the plane of the Galaxy, is between two hundred thousand and three hundred thousand light years. The center of the Galaxy is in the direction of galactic latitude 0°, galactic longitude 327°, and it is so remote that a very asymmetrical apparent distribution is imposed on the globular clusters, which thus appear concentrated in Scorpio, Sagittarius, and the surrounding constellations. Also there appears to be a decided concentration of other remote and highly luminous objects in the same region

of the sky, probably the result of the great depths of the Galaxy in the direction of the center, rather than of a real clustering of such objects around the center.

Since the globular clusters are probably good indicators of the form of the Galaxy, of which they are a part, we conclude somewhat tentatively that galactic objects lie in an irregularly circular and much flattened system—a discoidal affair populated by probably not less than 10^{11} stars (one hundred billion). Its dimensions may be greater or less than those of the surrounding and concentric system of globular clusters. It is our problem to discover the extent of the Galaxy by direct measurement, instead of continuing to base our estimates largely on the distribution of the globular clusters.

Increasing knowledge of the absolute luminosity of variable stars increases also their usefulness in measuring distances, whether inside the Galaxy, or outside, in globular clusters, Magellanic Clouds, and extra-galactic nebulae. It now appears that typical Cepheids, cluster type variables, long period variables and to a more limited extent novae and eclipsing binaries, can all be used in the work on galactic dimensions. Ultimately we may use also the planetary nebulae, the open clusters, peculiar types of variables, and stars of extraordinary spectrum and color in this work; and certainly the integrated magnitudes and angular dimensions of globular clusters and extra-galactic nebulae are among the most potent measuring tools, though they are only indirectly used in the present study of galactic structure.

In order to provide material for the general study of faint variable stars as bearing on the Milky Way problem, an extensive observing program was inaugurated about five years ago at the Harvard Observatory."[11]

This work is being carried on energetically, and several hundred new galactic variables have been found.

For purposes of study the Milky Way was divided into 240 star fields. An investigation has already been made by Dr. Shapley and Miss Swope of one of these fields, No. 185, situated in Scorpio and Ophiuchus. In this star cloud the periods of 26 cluster type variables were determined. The distance to the center of this cloud, derived from these variables, is about 47,000 light years, which is the same within admitted errors as the distance previously found for the center of the system of globular clusters, and as the center of the galactic system.

[11] Proc. Nat. Acad. Sci., **14**, 825, 1928.

It thus appears that in exploring the rich star cloud in Scorpio and Ophiuchus, as shown on Milky Way Field 185, we have been measuring a portion of the central nucleus of the Galactic System.[12]

Details of the Solar Neighborhood.—Several minor contributions to the structure of the galactic system have been made by different members of the Observatory.

King has discussed the possibility of a local cloud of absorbing matter. That large areas in the Milky Way are obscured by dark clouds is now a matter of common knowledge. King brought together considerable evidence in favor of the hypothesis that a local cloud of absorbing matter, extending from the sun to a distance of at least 100 light years, pervades our local cluster.[13]

Luyten has made a study of the nearby stars, those considered nearer than 10 parsecs; 104 such stars were found. Among the products of this investigation are, with certain assumptions: the sun's velocity through space is 25 km/sec; the total mass of the Kapteyn System is 1.4×10^9 times the sun's mass; number of collisions in the Kapteyn System is 1.4×10^{-13} per year.[14] The work was supplemented by a study of southern stars nearer than 25 parsecs.[15] Luyten has also made a study of the brighter M type stars,[16] of absolutely bright stars in the vicinity of the sun,[17] of groups of connected stars,[18] and of the proper motions of stars.[19]

The Magellanic Clouds.—It is evident that although great advance has been made in the solution of the problems involved in the dimensions of the galactic system, much time must yet elapse before all the material necessary for the completion of Shapley's investigations, outlined above, can be obtained.

[12] *Ibid.*, p. 830.
[13] H. C. 299, 1927.
[14] H. A., **85**, No. 5, 1923.
[15] H. C. 251, 1924.
[16] *Ibid.*, p. 273.
[17] H. C. 274, 1925.
[18] H. C. 298, 1926.
[19] H. C. 283, 1925; 293, 1926.

Meanwhile, even more rapid progress has been made in the study of the Magellanic Clouds, two isolated stellar systems in the far southern sky. It appears somewhat anomalous that distant systems can be investigated more readily than our own system of which we are a part. Our outlook, however, is rendered more complicated from our position within the galactic system. An outside view would have many advantages. If we might be placed at a distance of half a million or a million light years, so that we could view the galactic system as a whole, the problems as to size and form would be much more simple.

The Magellanic Clouds have the appearance of detached parts of the Milky Way. They are plainly visible to the unaided eye on a moonless night, but practically disappear in full moonlight. Like the Milky Way, these Clouds are composed of faint stars, nebulae, and clusters.

Much attention has been given to the Magellanic Clouds by astronomers, notably by Dr. Shapley. The accumulation of data concerning them was actively begun during the administration of Pickering. Photographs of both Clouds were obtained with various instruments soon after the establishment of the southern station at Arequipa, in 1891.[20] It was early recognized that certain features associated the Clouds with the Milky Way. For example, of all the stars known to be of the fifth type (Class O), having spectra with bright bands, about 80 are found near the central line of the Milky Way and more than 30 in the Magellanic Clouds.[21] Great numbers of variables also have been found in the Clouds, as well as in some globular clusters and in certain areas of the Milky Way, as described in Chapter XIII.

A relationship between the galactic system and the spiral nebulae, although often suspected, is not obvious. Nevertheless, some resemblances exist. Shapley has made a comparison of the spiral nebula Messier 33 and the Large Magellanic

[20] H. A., **26**, Part 2, 1897.

[21] H. A., **56**, 177, 1912; H. B. 801, 1924.

Cloud concluding that "These comparisons, though admittedly provisional, are sufficient to justify classing the Magellanic Clouds with the spirals." Since resemblances between the Magellanic Clouds and the galactic system have already been shown, it seems evident that all these varied groups, if not always to be regarded as sister systems, may at least be accepted as cousins or second cousins in the celestial family.[22]

Shapley issued in May 1924 the first of a series of papers treating of the distance, size, and structure of the Magellanic Clouds. Preliminary investigations by Hertzsprung and Shapley had revealed that the parallaxes of the Clouds were not larger than a few hundred thousandths of a second of arc, far beyond the reach of trigonometric methods. The stars, also, are too faint for the determination of spectroscopic parallaxes. Photometric methods must therefore be employed. Fortunately, there was no lack of Cepheid variables. The early photographic magnitudes of Miss Leavitt, although in general good, needed a change of about one magnitude in the zero point. An elaborate revision of the early magnitudes was carried out, and new sequences of stars were added in the Small Magellanic Cloud. In all, photographic magnitudes were determined for 25 sequences in the Small Cloud, including about 400 stars, ranging in magnitude from 6.73 to below the seventeenth magnitude.

The determination of the distance of the Small Cloud was made by a comparison of the apparent photographic median magnitude with the absolute median magnitude deduced from the period-luminosity curve. The mean value of the distance is approximately 100,000 light years, with an estimated probable error of 15 per cent. The average angular diameter of the Cloud is $3^{\circ}.6$, which corresponds, with the above value of the distance to about 6000 light years.

Accepting R. E. Wilson's determination of the motion of the Small Cloud in the line of sight as +170 kilometers a second, Shapley points out that this corresponds to 165 parsecs in

[22] H. B. 816, 1925.

a million years. On the assumption that the velocity of recession has been the same in the past, he finds that the Small Cloud was in or near the plane of the Milky Way in the year -1.9×10^8, or 190,000,000 years ago. This result leads to interesting possibilities in regard to some of the star clouds of our present Milky Way.

The brightest stars in the Small Cloud have apparent photographic magnitudes between 10 and 12. It follows from the above parallax that their absolute magnitudes exceed -5.5, occasionally as high as -7.0, fifty thousand times as bright as our sun.[23]

Many additional results of striking interest were obtained later in regard to stellar magnitudes in the Small Cloud. Shapley finds that in this Cloud occur some 300 stars, whose visual absolute magnitudes are brighter than -7.0, and 260,000 stars with absolute magnitudes brighter than zero. A luminosity curve for the giant stars was determined with the assistance of Miss Ames from a study of 6,800 stars, in six regions each containing a magnitude sequence. A curve for each region was derived, as well as the general luminosity curve for the whole. The brightest stars in the Small Cloud were found to be photographically between 10.5 and 13.5, corresponding to absolute photographic magnitudes -7 and -4. The absolute magnitude zero corresponds to the apparent photographic magnitude 17.5. Integrating the light of all the stars, except those fainter than 18.0, the total apparent photographic magnitude appears to be about 2.0, possibly no greater than 3.0. The total absolute magnitude of the Small Cloud, excluding stars fainter than 18.0, is of the order of -15.[24]

Similar investigations were made of the Large Magellanic Cloud. Using methods similar to those referred to above for the Small Cloud, Shapley found the provisional parallax of the Large Cloud to be $0''.000029$. This would place the Large

[23] H. C. 255, 1924.
[24] H. C. 260, 1924.

Cloud at a distance of 34.5 kiloparsecs, or 112,000 light years, somewhat more distant than the Small Cloud. The average diameter of the Large Cloud is $7^\circ.2$, corresponding to 4.3 kiloparsecs, or nearly 14,000 light years. Its radius is thus about ten times the probable distance of the earth from the Orion Nebula. The distance between the two clouds is about 12 kiloparsecs, or nearly 40,000 light years, a distance greater than that from the earth to the Hercules Cluster.[25] Later work by Shapley, Miss Sawyer, and Miss Ryder, as yet unpublished, indicates a somewhat larger parallax for the Large Cloud.

The completion of five sequences of comparison stars in the Large Cloud, and the derivation of the parallax as given above, permitted the determination by Shapley of the absolute magnitudes of the various objects in the Cloud. The absolute magnitudes for 9 stars of the P Cygni type lie between -3.2 and -7.9. The absolute magnitudes of at least 20 invariable stars appear to be brighter than -8. Miss Leavitt found 808 variable stars in this Cloud, and others have been added by different observers. Five clusters surely globular, and two or more others doubtfully so, are found in the Large Cloud. The mean apparent photographic magnitude of the five globular clusters is 9.2, corresponding to the absolute photographic magnitude -8.5. This probably corresponds to an absolute visual magnitude of -9.1. The mean absolute visual magnitude found for globular clusters outside the Magellanic Clouds is -8.8. The agreement is as close as could reasonably be expected. The most striking object in the Cloud is 30 Doradus, the well known nebula N. G. C. 2070. The integrated absolute magnitude is about -14, making it ten or eleven times brighter than the Orion Nebula. The diameter of the brighter portions of 30 Doradus is 20 parsecs, and of the whole nebula, including the faint extensions, about 40 parsecs. Placed as near to the earth as the Orion Nebula, it would have an apparent magnitude of -7.5, and would cast strong shadows on the earth.[26]

[25] H. C. 268, 1924.
[26] H. C. 271, 1925.

In a later discussion of the Magellanic Clouds, the absolute magnitudes and diameters of 108 diffuse nebulae in the Small Cloud were given. The average absolute magnitude for the 108 nebulae is -5.3 ± 0.1. The average linear diameter of 106 nebulae is 5.0 ± 0.2 parsecs. A second list increased the number of nebulae in the Small Cloud by 170.[27]

The period-luminosity curve hitherto used was referred to median visual magnitudes. Since its practical use had become almost exclusively photographic, a well determined photographic period-luminosity curve was needed. The visual curve published in 1917 was based on material derived from globular clusters and the Small Magellanic Cloud. For the new determination of the photographic curve, Shapley, aiming at more homogeneous material, used only photographic data derived from the Small Magellanic Cloud. The reduction was based on 107 variables well scattered throughout the Cloud.[28]

In the study of the Magellanic Clouds, it is important to distinguish between the stars comprising the foreground and those belonging to the Clouds. The conclusion drawn from a study of this problem, based largely on the spectral composition of the foreground and of the brighter objects in the Clouds, was that we have no definite evidence of stars in the Small Cloud brighter than apparent magnitude 10.0, or absolute magnitude -7.5, whereas in the Large Cloud it is probable that 20 or 30 stars are brighter than apparent magnitude 9.0. Further spectroscopic investigations on this subject are planned.[29] Dr. Shapley was assisted in one or more of his later papers on the Magellanic Clouds, referred to above, by Harvia H. Wilson, Issei Yamamoto, and Margaret L. Walton.

Extra-galactic Systems.—The method of determining distances by the use of the period-luminosity curve of variable and other stars, made of universal application by Shapley, has been used to extend our knowledge of extra-galactic objects

[27] H. C. 275, 276, 1925.
[28] H. C. 280, 1925.
[29] H. C. 288, 1925.

revealed to us by the telescope. By such means it has been found, especially by Hubble of the Mount Wilson Observatory, that the spiral nebulae lie far beyond our local system, and that they form independent stellar systems, whose distance from the earth must be expressed in many cases in millions of light years. Our nearest neighbors among stellar systems are the Magellanic Clouds at about a hundred thousand light years. A very few bright spirals, such as the great spiral nebula in Andromeda, probably are somewhat less distant than one million light years. Accepting the general truth of these results, it appears that the faintest spirals which can be photographed must be situated at a distance not less than one or two hundred million light years.

Such in general is the size of our visible universe, so far as we have the means to extend it at this time. The Harvard Observatory has long been at work in the effort to make a survey of the sky, using long photographic exposures, in order to reach the faintest extra-galactic objects possible. The Bruce 24-inch doublet has been found well suited to this survey, although the great reflectors may well extend the investigation to fainter objects in special limited areas. The nature of many of the structureless nebulae, which are shown on photographs of long exposure, is not yet known.

Shapley has made a classification of the extra-galactic nebulae, suited to the work of the Bruce telescope, which has probably photographed more nebulae than any other single instrument. He has chosen as the significant descriptive information for extra-galactic nebulae: position, total magnitude, size, form, orientation, concentration, and, for a few, an indication of irregularity in form or concentration, and the presence of spiral structure.[30]

Out of more than twenty thousand catalogued extra-galactic nebulae, more than a fourth have been found and described at Harvard. Nearly ten thousand more have been recently discovered on Harvard photographs but not yet completely studied

[30] H. B. 849, 1927.

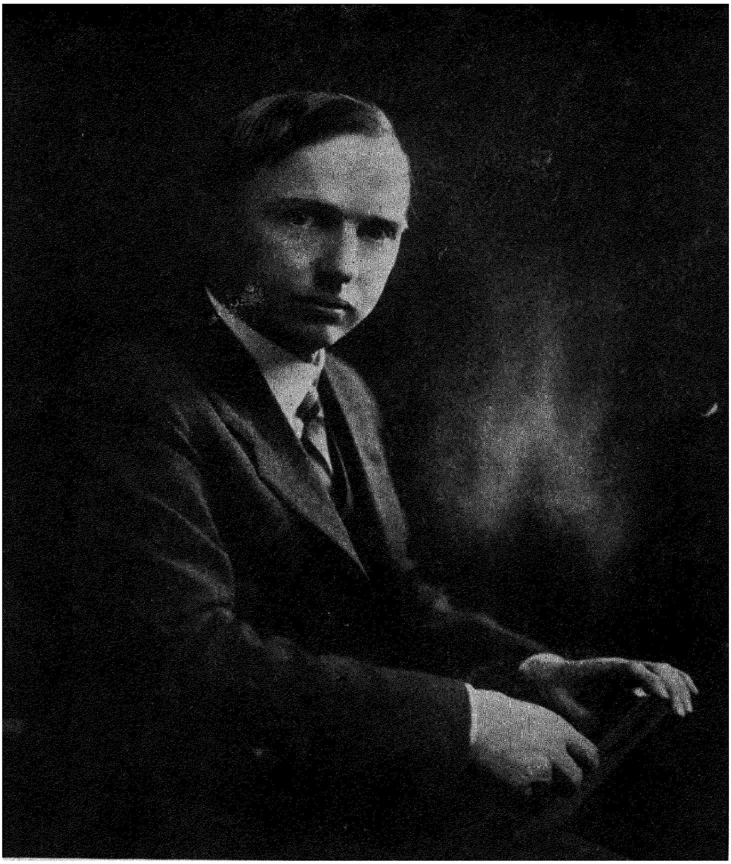

PLATE XIX.—HARLOW SHAPLEY.

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and published. Shapley found 850 nebulae on a single Bruce plate, of six hours exposure, at $22^h\ 40^m$, $-45°$, in a region of 30 square degrees.[31]

Shapley and Miss Ames obtained especially interesting results in the study of a cluster of bright spiral nebulae at approximately $12^h\ 20^m$, $+13°$. The distance to the center of the whole group is given as probably of the order of ten million light years, and the diameter of the group, as two million light years. No better example can be given of the magnitude of the problems presented to modern astronomers, when it is considered that this cluster is one of the brighter groups of the extra-galactic nebulae. As a by-product of this investigation, Shapley found that, in confirmation of his earlier investigations and of the work of Lundmark and Lindblad, the scattering of light in space, if any, is too small to be appreciable.[32]

The term "island universes" has been applied to these outlying stellar systems, such as the Magellanic Clouds, and the great spiral nebula in Andromeda. The term is objectionable since "the universe" is one, but its use is unimportant if the truth is understood. Our "universe," the galactic system, appears at present to be by far the largest system known. As Shapley has aptly expressed it, where other systems are known as islands, the galactic system is a continent. Yet such a system as the Andromeda Nebula, with a diameter of some 45,000 light years, is no mean rival; while, far more distant and appearing only as faint flecks of light, equally large, or even greater systems may exist. It is evident however, that, whether we live in a limited universe or not, there is a definite limit beyond which our observations cannot reach. Within this realm lies the province of astronomy; what exists beyond may well be left to the mathematician and the metaphysician.

[31] H. B. 784, 1922.
[32] H. C. 294, 1926.

PART III

BIOGRAPHICAL SKETCHES

CHAPTER XVI

THE BONDS

The first four directors of the Observatory, William C. Bond, George P. Bond, Joseph Winlock, and Edward C. Pickering, held the office respectively for 20, 6, 9, and 42 years. They all died in office. During the brief intervals that elapsed between successive directors, the Observatory was in charge of the ranking assistant. The fifth and present director of the Observatory (1927) is Harlow Shapley.

The early history of the Observatory is largely a record of the personal achievements of the Bonds, who controlled its destinies for 26 years. That it became a research institution rather than a teaching department of the College is due in no small degree to them. A brief account of their lives is given in the present chapter.

William Cranch Bond, 1789 to 1859; Director, 1839 to 1859.—William Cranch Bond was descended from a prominent family of Cornwall, England. His mother's family, from whom he received the name Cranch, was from the neighboring county of Devonshire. His father, William Bond, visited this country in 1784, and lived for a time in Boston, where, in 1785, he was made a free citizen of Massachusetts by special act of the General Court. He chartered a brig and came to Boston again in 1786, bringing his family. Later he established himself in Falmouth (now Portland, Maine) and engaged in the business of shipping lumber to Bristol, England. This venture, however, was unsuccessful, and in 1790 he removed to Boston and began business as a watch- and clock-maker, a trade he had learned in London. When Mr. Bond brought his family to Massachusetts, he had two children living, two having died in infancy. In America two more children were

born, a daughter, Hannah Cranch Bond, and, sixth and last, William Cranch Bond.

William Cranch Bond was born in Portland on September 9, 1789. His childhood and youth were periods of disappointment, hardship, and struggle, due to poverty. The business established by his father in Boston developed very slowly and needed all the assistance he could give. He was obliged to leave the public schools at an early age. To a sensitive and studious boy this was a heartbreaking sacrifice. But however hard his daily routine labor, he found some time for study and improvement. He had a rare mechanical ability, which was manifested in early childhood by his skill in making toys and other things of special interest to boys.

At the age of fifteen, while actively employed in the work of his father's shop, Bond constructed a useful chronometer. He had no model, but followed a description, which he had found in an old French book, of the chronometer used by the navigator Perouse. In the absence of a suitable spring he used weights, so that the chronometer was serviceable for use only on land. But in 1812, at the age of twenty three, he made an excellent ship's chronometer. His attention was irrevocably fixed on astronomy by the remarkable total eclipse of the sun in 1806, when he was seventeen years of age.

The following extracts from a communication made by his son, George P. Bond, to Hon. Edward Everett in 1859, just after the death of his father, throw light on the early struggles of William Cranch Bond:

I have always understood that his situation up to manhood, and even for years after, was one of peculiar trial and hardship. It was at this period of life, usually so full of animation and buoyancy, that he speaks of himself as "nearly heart broken and in despair of ever being able to accomplish anything." The expression bespeaks the sensitiveness of his disposition, and a dejection unnatural in one so young. His mother, Hannah Cranch, as was fit, was ever the confidante of his plans, and the consoler of his distress. She was a woman of well-cultivated mind and high excellence of character; one who could sympathize in his high aspirations, though she could not relieve the pressure of adversity.

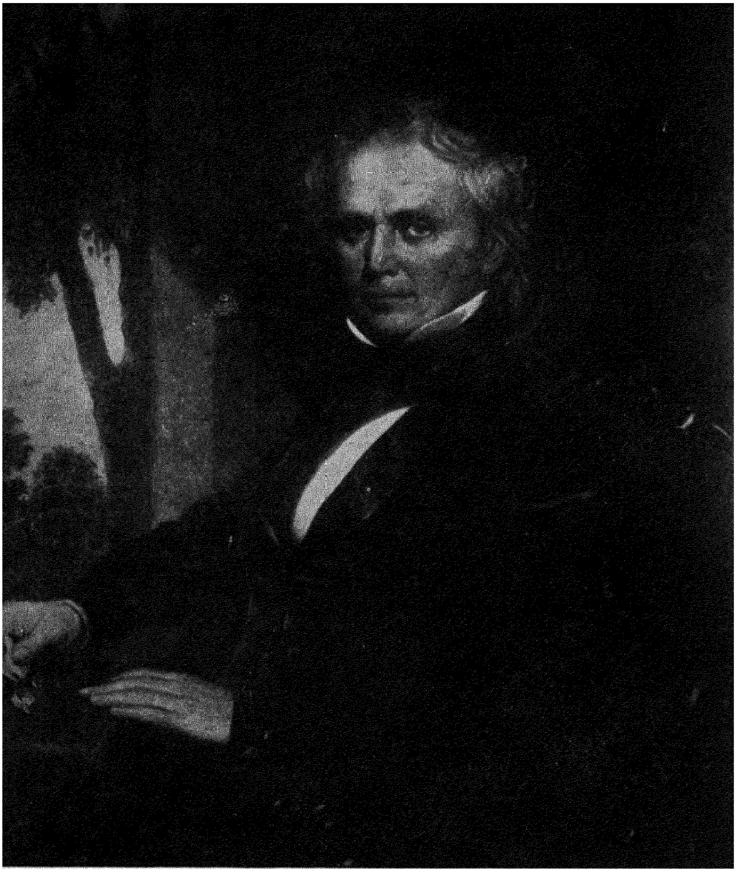

PLATE XX.—WILLIAM CRANCH BOND.

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In his boyhood a modest reserve and a quick sensitiveness were as prominent as in later life; yet there was a resolute spirit beneath this veil, or he would never have risen superior to frowning fortune. This simplicity of manner and shrinking from ostentatious display did not wholly conceal from his playmates a consciousness of superior capacity; he could be silenced easily, but rarely diverted from his purpose. A design once formed in his mind seemed to become a part of his very being, and was pursued with an unfaltering aim. To this invincible perseverance he owed everything. It is not for us to condemn his persistence, sometimes beyond the bounds of reason, in his original convictions. Whatever he accomplished was done in a quiet, unobtrusive way; but if opposed, a determined, persevering energy was manifested, equal to any emergency, and seldom to be disappointed of its end. These are said to have been the traits of his boyhood—they certainly characterized his after life.

His first astronomical apparatus was a sundial and pieces of string held at arm's length, with which he plotted the stars and comets, after the fashion of Ferguson. These were succeeded by other contrivances better adapted to the purpose. It is a fact not without interest that for many years preceding the war of 1812, the period of our greatest commercial prosperity, the "rates" and "errors" of nearly all the chronometers employed in the foreign trade of Boston were derived from instruments made by his hand.

The history of his (independent) discovery of the Comet of 1811 shows him at that time as an attentive observer of the heavens. He had previously, for want of a telescope, been in the practice of going to a deep well, and, shading his eyes from stray light, would direct his eyes toward the bottom for some minutes, and with this preparation faint objects among the stars were more easily distinguished. Instead of attempting to acquire reputation from the discovery, he was so careless on this point that it took months for the intelligence to travel four miles to Cambridge. On the other hand he applied himself most industriously to collecting observations with such apparatus as he could command. To watch the motions, and record the positions of the heavenly bodies, was an occupation perfectly congenial to his tastes, which evidently brought with it its own reward. It was his constant practice, from the time when he first came into possession of appropriate instrumental means, to record astronomical phenomena, often with no other apparent motive than a love of the occupation. For thirty years this was done, not merely without compensation, but to his manifest pecuniary disadvantage. This consideration, it is probable, never entered his mind.

In this period we find him zealously tracing the courses of comets, collecting observations of lunar culminations, occultations, and eclipses of the Sun, determining by different methods the position of his observa-

tory and connecting it by trigonometric surveys with neighboring points, and in other ways evincing the strength of the ruling passion by the sacrifices which were made to gratify it. Nor was his attention confined to astronomy; the kindred sciences of meteorology and magnetism were not neglected. Even on his journeys it was his custom to take with him a sextant and artificial horizon and a chronometer to find the latitudes and the longitudes of the places visited.

The longitude of his observatory in Dorchester, adopted just thirty years since, agrees precisely with the latest determination of the position of the observatory of Harvard College, allowing for the difference of meridians. The latitude also presents as exact an accordance as could be attained with the instruments in his possession, confirming his remark: "I was satisfied that no repetitions with the instruments would have given me greater confidence in the results." In the first house which he owned (in Dorchester) the only parlor was sacrificed to science, and forthwith converted into an observatory. A huge granite block, some tons in weight, rose in the centre of the room, and the ceiling was intersected by a meridian opening. My recollection will just carry me thirty years back to this room and its mysterious paraphernalia. I can recall, too, in the garden and neighboring fields the stone blocks for the support of instruments, meridian marks, etc. Like the men of old, wherever he sojourned a stone was set up as a memorial. His antipathy to an insecure foundation many would have thought extravagant: the tremor of an instrument would annoy and fret him as a harsh discord does the cultivated ear of the musician.

Every year, as his means allowed, some addition was made to the resources for observation; but adversity still waited on him, and he was obliged, as a constant practice, after the whole day had been devoted to business, to spend hours at his work bench. He made it, in fact, a rule of life to earn enough by his nightly labor at his profession as a watch maker to meet the current household expenses. That so much industry and application should have failed in placing him in a position of competence will not surprise any one acquainted with his methods of conducting business transactions, for which, as far as his own pecuniary advantage was concerned, he had no capacity. The making of a good bargain was to him the most incomprehensible of problems.

Between 1825 and 1830 Bond made an investigation of the comparative rates of marine chronometers at sea and on land. He established the fact, at that time not understood, that the chief element in their differences in rates was the variation of temperature. His appointment by the United

States Government, in 1838, to cooperate with the expedition of Lieutenant Commander Charles Wilkes, was a striking recognition of the accuracy and value of his work. Without regard to the salary he was to receive or the amount of labor involved, he undertook to rebuild his Dorchester observatory in order to make the results worthy of his own ideals. The following year, 1839, through the direct personal influence of President Quincy, he was persuaded to transfer his equipment to the Dana House Observatory and undertake the duties of Astronomical Observer to Harvard University.

At the date of this interview the President found Mr. Bond well established in a profitable manufacturing business, happily situated in his domestic and neighborhood surroundings, with an avocation fascinating enough to occupy all his leisure, and a fame extensive enough to satisfy his own modest estimate of his abilities. There was no pecuniary betterment for Mr. Bond in the suggested change. Mr. Quincy could only offer him what he had already, a family domicile; so that the proposal might warrant an adaptation of Sydney Smith's famous phrase, and be described as an invitation to come to Cambridge and "cultivate astronomy upon a little oatmeal." In so phrasing it there is no disparagement of the College; it was the day of small things, of pennies not dollars, in the College treasury. But the event speaks the praises of Mr. Quincy, whose sagacity was unfailing, and before whose persuasiveness and energy difficulties in administration were wont to give way, and of Mr. Bond, whose unselfishness and loyalty to science were proof against pecuniary considerations.[1]

For nearly five years, while Bond remained at the Dana House, the observations in large part were meteorological and magnetic, although the Observatory had been regarded from the first as astronomical. Bond, however, made many observations of occultations, eclipses, and comets. The equipment was not such as to encourage the expansion of the astronomical program. Added to this is the fact that, since he received no salary from the University, Bond was obliged to carry on his business in Boston, in addition to the obligations he had assumed with the Government of the United States. During

[1] D. W. Baker, "History of Harvard College Observatory, 1840–1890," Boston Traveler, 1890.

the last part of this period, also, his time was largely taken up with the plans of the new Observatory and its equipment.

A new period began with the mounting of the large refractor in 1847. The public expected important observations and discoveries from the use of this instrument, then unsurpassed in quality by any telescope in the world. Bond fully appreciated the responsibility of his position. A long series of observations was begun on the members of the solar system, on comets, and on other important celestial objects, especially the nebulae. The results were sufficient to bring the Observatory to the attention and respect of the astronomical world. No further proof is necessary than his election as the first American Foreign Associate of the Royal Astronomical Society, an honor which he received in 1849.

A detailed account of the activities of the Observatory during his administration is given by Bond in his Annual Reports. The first report, that for 1846, soon after the opening of the new Observatory, contained information about the lens for the large refractor, and a new transit circle which had been ordered from Simms, of England. The report shows that moon culminations and star transits had been observed at all hours in connection with the observations made elsewhere by the United States Coast Survey. Of special importance at that time were observations of transits of stars in the prime vertical for the determination of the latitude of the Observatory. Observations of comets, four of which were found independently by George P. Bond, and the computation of their orbits, together with meteorological and magnetic observations, show the indefatigable activity with which Bond and his son and a few volunteer assistants carried on the work of the Observatory, even before the arrival of the principal instrument. The discovery of the dark ring of Saturn soon after the arrival of the 15-inch refractor, and later of an eighth satellite of that planet, demonstrated the high quality of the telescope. Detailed examinations of surface markings of the sun and planets, and of the appearance of

comets, clusters of stars, and nebulae served also to test the quality of the lens and the ability of the observers.

In the midst of so much discovery, it is not surprising that Bond's enthusiasm to make the most of the new telescope should have led him into an error of observation. In a letter to President Everett, September 22, 1847, he announced:

DEAR SIR:

You will rejoice with me, that the great nebula in Orion has yielded to the powers of our incomparable telescope! This morning, the atmosphere being in a favorable condition, at about three o'clock the telescope was set upon the Trapezium in the great nebula in Orion. Under a power of 200, the fifth star was immediately conspicuous; but our attention was very soon absorbed with the splendid revelations made in its immediate vicinity. This part of the nebula was resolved into bright points of light . . .

It should be borne in mind that this nebula and that of Andromeda have been the last strong-holds of the nebular theory; that is, the idea first suggested by the elder Herschel of masses of matter in process of condensation into systems.[2]

Bond goes on to state that the Herschels had been unable to resolve the nebula, and that Lord Rosse had also failed to resolve it until he used the reflector of 6 feet aperture, when he announced that:

I think we may safely say, that there can be little if any doubt as to the resolvability of the nebula. We could plainly see that all about the Trapezium is a mass of stars, the rest of the nebula also abounding in stars, and exhibiting the characteristics of resolvability strongly marked.

It must be remembered that at this time the spectral analysis of such objects was unknown, and that among astronomers the idea was general that the nebulae only awaited sufficiently powerful telescopes for their resolution into stars. Bond appeared to have some doubts regarding the accuracy of this communication to President Everett, for no mention is made of it in his annual reports or in public announcements.

To Bond and to members of his family is due the credit for the construction of the first really satisfactory chronograph for the

[2] H. A., I, cxxi, 1847.

automatic recording of star transits. The development of electric methods for longitude work, in cooperation with other workers in the same field, was promoted at Cambridge, which accordingly became the recognized center for longitude determinations.

At the close of William C. Bond's life, the Observatory had been brought into a state of high efficiency and occupied an enviable position in the astronomical world. Although still cramped by insufficient funds, it had been saved from the possibility of failure. The results showed the wisdom of Quincy's policy in asking Bond to direct the early years of the Observatory. The value of his services was everywhere recognized, as were his peculiar genius, energy, and devotion.

Bond was fortunate in his family life. His first wife was his cousin, Selina Cranch, whom he married on July 18, 1819, at Kingsbridge, Devonshire, during a visit to England. She was the mother of his six children, William Cranch, Jr., Joseph Cranch, George Phillips, Richard Field, Elizabeth Lidstone, and Selina Cranch. His wife died in 1831, and later he married her elder sister, who devoted herself to him and his astronomical ambitions, making every possible sacrifice to aid his endeavors. His children, also, were equally devoted to their father. Indeed his passion for astronomical observation and his boundless energy and enthusiasm seemed to sweep away all opposition and enlist cooperation.

Some account of Bond's scientific work is given earlier in this volume. In addition to his election as the first American Associate of the Royal Astronomical Society, he received the honorary degree of A.M. from Harvard University in 1842; he was a member of the American Academy of Arts and Sciences, and the American Philosophical Society; a corresponding member of the Institute of France, and of the Accademia dei Lincei. On his death in 1859, his friend Professor Benjamin Peirce, of Harvard University, the foremost American mathematician of his day, presented an appreciation of his life to the American Academy of Arts and Sciences:

. . . During seventeen years I have been Mr. Bond's colleague in Harvard College, and this interval comprises the whole period in which he had any favorable opportunity of astronomical observation. But his love for the science had been shown long before he came to Harvard, and even a quarter of a century earlier he made a careful survey of the Greenwich Astronomy, at the request of President Farrar, with direct reference to the superintendence of the erection of an Observatory at Cambridge . . . When Mr. Bond returned from England he set up a small Observatory of his own, where he undertook the observation of occultations and eclipses. It was here that he developed one of the finest elements of genuine enthusiasm and true genius, that of accomplishing much with small means . . .

When . . . he was drawn to Cambridge by the strong hand of President Quincy, when the cause of the Observatory was undertaken by the unflinching and irresistible vigor of my friend, Mr. J. Ingersoll Bowditch, when even the heavens came to our assistance, and that wonderful Comet of 1843 . . . excited most opportunely a universal interest in celestial phenomena—it was then apparent that the affection for Mr. Bond was the chief strength of the occasion, and to that were we mainly indebted for the successful attempt to obtain the unrivalled equatorial of the university and to lay the foundations of the Observatory. In the history of American science there is no more memorable epoch . . .

The astronomical researches of Mr. Bond while at the Observatory are so recent that I need only allude to them. By the habits of his life his attention was especially drawn toward the improvement of the instrumental means of observation. Hence, we have from him, and under his administration—first, the ingenious observatory-chair of the great equatorial; second, the spring-governor . . . ; third, the application of photography to the Sun, moon, and stars.

In his original investigations he naturally restrained himself to those forms of observation which were fully within the reach of his own resources. He did not, therefore, seek those inquiries which could only be accomplished by long, intricate, and profound mathematical computations . . . But when observations were required which must be passed over to the computer, his skill was not wanting to the occasion. Thus, in conjunction with Major Graham, he made that choice series of observations from which the latitude of the Observatory was determined. His observations, and those made under his administration, upon the nebulae of Orion and Andromeda; the interesting discoveries as to their revolution and peculiar configuration; the researches into the physical aspects of the different planets, and especially those upon the Saturnian system; and the remarkable discoveries of the inner ring, and of the fluid[3] constitution of the

[3] Both the Bonds and Professor Peirce believed the rings of Saturn to be fluid.

rings, and of the eighth satellite, need only be named. They are known to all; they have passed into the text books of astronomy, and our children's children will be familiar with the name of Bond.[4]

George Phillips Bond, 1825 to 1865, Director, 1859 to 1865.—George P. Bond, son of William C. Bond, was born in Dorchester, May 20, 1825. He was graduated from Harvard College in 1845. His childhood and youth were passed in an astronomical environment so intense as to dominate all other influences. Some of his impressions of the life at Dorchester have already been given in the sketch of his father's career. A clear conception of the characteristics of his youth and manhood may be gained from the following extracts of notes prepared at the request of Professor Holden by his daughter Elizabeth Bond, of Cambridge:[5]

We have few reminiscences of his early childhood, but I am told that he was peculiarly gentle and lovable, a tractable, intelligent pupil, in favor both with teachers and playmates . . . A quiet, reserved, self-contained boy, he, no doubt, did not easily make intimate friends, though he won the respect and the liking of all . . .

He was passionately fond of out-of-door life and sport, a true Englishman in his love of hunting and fishing. Until his health began to fail he went each year on some shooting expedition, either to Maine for deer and moose, or to the shores of Cape Cod for wild duck. He was deeply interested in ornithology, and when a lad had, for a time at least, contemplated devoting his energies to the study of some branch of Natural history rather than to astronomy. His elder brother's death, however, left him no choice but to take that brother's place and to become the support and colaborer of his father. It was not without reluctance that he resigned his own special taste to turn his attention exclusively to the stars. So long as he lived it was his favorite recreation to read works on ornithology, or to watch the birds and note their plumage, song, and habits . . .

Some of the sweetest memories of my childhood are connected with the happy hours spent in the garden or the fields with my father . . . He was naturally fond of children, and showed rare tact in gaining their love and confidence . . . When a mere baby, not more than three years old, I can remember being held out of an open window in my father's arms—

[4] Proc. Amer. Acad., 4, 163, 1859.

[5] Edward S. Holden, Memoirs of W. C. Bond and G. P. Bond, 48, 1897.

as far as he could stretch safely—to see an eclipse of the Moon. It was a winter's night, and very dark and cold, and I was as much alarmed as interested by the weird spectacle, so it made an impression on me.

The early death of his wife was a severe blow to his sensitive nature. She was a woman of a singularly sweet, gentle disposition, and their short married life had been very happy, though clouded by the shadow of her fatal illness. In the course of eleven months, he lost his youngest child, his wife, and his father, and a serious fit of illness developed in himself, the seeds of the disease which was to cut off his own life in a few short years. My mother died in December, 1858.

In 1859, on the death of his father, he was appointed director of the observatory, and it was only then that the real difficulty of carrying on the work with the insufficient means at the disposal of the observatory became evident. The chronometer and clock business of the firm of William Bond & Son was prosperous, and my grandfather had been able to supply any pressing need from his own purse. But my father had no private resources at his own disposal, and the sums supplied him by the funds of the institution or the liberality of a few Boston friends, were wholly inadequate to meet the wants of the observatory. Expenses were curtailed as far as possible, especially those of his own household, but the weight of care and anxiety pressed more heavily with each succeeding year. My father felt in honor bound to keep the work up to the highest standard, while the bitter jealousy and persistent enmity of certain disappointed candidates for the office he held left him no repose of mind or body. The outbreak of the war was a terrible blow to the progress of science, and for a time he was almost hopeless about the condition of the Observatory. Money was scarce, and as none knew what a day might bring forth, donations toward astronomy were, of course, more scanty than ever. Still there were generous friends who gave ungrudgingly. Among them I should specially mention J. Ingersoll Bowditch, the loyal, liberal-minded friend of father and son, Hon. Josiah Quincy, Robert Treat Paine, and a few others . . .

Of his own time, strength, and energy, my father gave without stint . . . When again and again warned by friends that fatal disease was approaching—or rather advancing—with hasty steps, and that the only remedy was rest, his answer was, "That is the only remedy I cannot use; I have a work to do and must do it if I can, whether I am to live or die." . . .

No doubt his life was shortened by the privations and exposure forced upon him by the state of the country. The Observatory was not properly heated, and the rooms he was obliged to visit were often bitterly cold and draughty . . .

Before his illness he travelled much among the White Mountains, visiting wild, unfrequented spots. He made maps of the region, which

until recently were the standard authority for all the guide books of that section . . .

In person he was rather tall (a little under six feet) and slender, becoming of later years, painfully thin. His hair was wavy and very dark, if not black; his complexion pale, and his eyes of the deepest blue . . . He was most anxious to live to complete his work on the Nebula of Orion, being unwilling that it should be published in an unfinished form, without his own supervision. He worked upon it after he was too feeble to hold a pen, until the day before his death.

Professor Asaph Hall, for many years a leading member of the Naval Observatory at Washington and the discoverer of the satellites of Mars, was an assistant at the Harvard Observatory during the years 1857 to 1862. He was engaged as an assistant by W. C. Bond at a salary which, although extremely small, made it an inducement for him to come to Cambridge. The opportunities for mathematical studies at the University and for practical observation at the Observatory were the special attractions. Some extracts from a statement by him of his experiences during those years throw interesting light on the Bonds, and incidentally on Mr. Hall himself and the struggles of a poor but ambitious young astronomer of that day. The statement was written in 1895, at the request of Mr. Bond's daughter.[6]

My wife and I reached Cambridge in the last part of August, 1857. We had a kind reception from Professor W. C. Bond. Professor G. P. Bond was absent on a visit to New Hampshire. I was set to work making observations for time, to read the chronograph sheets, to work out the instrumental constants, and to compare and rate the chronometers. Professor Bond was very kind and pleasant, so that under his guidance I made good progress. I worked hard and spent most of my time at the Observatory. After a month or six weeks Professor G. P. Bond returned. He seemed a little surprised to find an assistant in the observatory, and doing so much work. He had a free talk with me, and found out that I had a wife, twenty-five dollars in cash, and a salary of three dollars a week. He told me very frankly that he thought I had better quit astronomy, for he felt sure I would starve. I laughed at this, and told him my wife and I had made up our minds that we were used to sailing close to the wind, and felt sure we would pull through. He appeared satisfied.

[6] *Op. cit.*, 77, 1897.

Afterward I worked a great deal with him as an assistant for recording and reducing his observations.

Professor W. C. Bond was in poor health when I entered the observatory, and died early in 1859 . . .

Professor George P. Bond succeeded his father as director. He was very active during my stay at the observatory in making experiments and observations in photographing the stars, in photometric observations, and in his work on the nebula in Orion. His work on the Comet of Donati, in 1858,[7] was a very complete investigation of the physical appearances of that great comet. I assisted Professor Bond in all this work and in the reductions, besides pushing on my own studies. I have a very distinct recollection of how cold my feet were when he was making his winter observations on Orion. I sat in the small alcove of the great dome behind a black curtain and noted on the chronometer the transits of stars when Professor Bond called them out, and wrote down the readings for declination. For some of the brighter stars which were observed on the chronograph I had to note the click of the key, and my record was compared with that of the chronograph down stairs. I became so expert that the difference rarely exceeded a tenth of a second, and for the fainter stars the chronograph was not used. Sometimes I was called to the telescope to examine a very faint star, or some configuration of the nebula. Professor Bond had one of the keenest eyes I have ever met with. His work on this great nebula forms an epoch in its history . . .

Professor Bond indulged great hopes that photography would render much aid in the measurement of double stars and clusters.

Professor George P. Bond had received, evidently, a much more complete training than his father. While he had not that familiar knowledge of mathematical formulas which distinguishes the professional mathematician, he had what is better: He was thoughtful and ingenious in his investigations. He liked to study things in their actual relations, and had the spirit of an inventor. His style of mind led him to original work. He was the first to apply the method of mechanical quadratures directly to the rectangular equations of motion, a method afterward discovered and elaborated by Encke. He was among the first to take up photography and carry it out to practical results. His ability has not, I think, been sufficiently recognized; but he was a shy and reserved man, made so, perhaps, by the condition of his health.

Although I was poor and worked hard, I was not sick a single day during those five years at Cambridge. They are for me a pleasant remembrance of hope and struggle, and I was fortunate in having to deal with two such honorable men as the Bonds."

[7] H. A., **3**, 1862.

On the death of William Cranch Bond, the question of his successor became at once urgent. George P. Bond was not the only candidate. Professor Benjamin Peirce was among the aspirants. His high talents in mathematical and astronomical research made him one of the foremost figures in American scientific circles. Nevertheless, the Corporation selected Bond, and the choice was evidently a wise one. The Observatory had already made for itself an enviable reputation, chiefly by work of a high order on observational lines, and Bond had been intimately associated with his father in much of this. The discovery of Bond's Dusky Ring of Saturn and the eighth moon was as much his work as that of his father. Professor Peirce was not an observer. At that time, especially, observations of the best class were the chief duty of the director as well as of the staff. Bond's abilities in this line were unequalled in America and unsurpassed anywhere. Also, as stated elsewhere, his mathematical ability was more than ordinary, and his originality, energy, and devotion to his work were above praise. Also he was thoroughly familiar with the work and needs of the Observatory. Professor Peirce, however, was deeply offended by Bond's selection, and an estrangement which embittered Bond's career occurred between them. An unfortunate and unfair antagonism was shown by Professor Peirce and a few other scientific men who sympathized with him. Bond attempted to heal the matter by writing a conciliatory letter to Mr. Peirce, but received no reply.

Once aroused by what appeared to him an injustice, Bond was capable of assuming a determined, and possibly somewhat obstinate stand. Like his father, he could not be driven by adverse criticism which appeared unjust to him, but on the contrary was impelled to more determined action. This is shown by the intense labor with which he devoted himself to his observations of the Orion Nebula because he believed that his father's study of it had been unduly criticized by Struve; Bond felt a criticism of his father more intensely than one of himself.

Probably the work which brought Bond his greatest reputation was his monograph on the comet of Donati, the Great Comet of 1858, which is given in full in the third volume of the Annals of the Observatory. Holden says:

> Nothing of this excellence had ever been done before; now that we have photography to aid us, nothing of the sort will ever be done again. It stands alone, and is and will remain unique of its class.[8]

The publication of this work won general approval both at home and abroad. The drawings of the comet reveal Bond not only as a most exact observer, but as an artist as well. The memoir gained him the award of its gold medal by the Royal Astronomical Society of Great Britain, the first presentation of the medal to an American astronomer. The medal was formally awarded at the meeting of the Society in February, 1865; the formal announcement did not reach Cambridge until a few days after Bond's death, but happily his friends in London had informed him a few weeks earlier that the award was to be made.

Of almost equal merit was his study, referred to above, of the nebula in Orion. The results are given in Volume V of the Harvard Annals. His object appears to have been twofold: to meet the adverse criticisms occasioned by his father's early paper on this nebula; and to leave a monograph on the subject that should be above criticism. Bond began this investigation in 1857, but interrupted it for the work on Donati's Comet, and did not entirely finish it before his death. The results were completed for publication by Professor Safford. Bond's monograph of the nebula was later checked with the 26-inch telescope at Washington by Professor Holden, who has expressed enthusiastic appreciation of the accuracy and beauty of Bond's work. In a paper published in 1880, Holden states: "I am acquainted with but one drawing of the nebula which is entirely above criticism—that of the late G. P. Bond."

Professor Holden also checked and verified Bond's list of 1101 stars in the nebula, and states that although made with a

[8] Holden, *op. cit.*, 267, 1897.

telescope of 15 inches aperture, it contained "almost every star visible in the much more powerful instruments used by Lassell, Lord Rosse, and myself." A severer test of the accuracy of the drawing of the nebula came with the introduction of photography. Perhaps no drawing of such an object before the days of photography will bear this test so well as Bond's drawing of the Orion nebula.

In his younger years, Bond sought assiduously for comets and independently discovered eleven, although it was found later that most of them had been seen at an earlier date in Europe. He computed the orbits of many comets, and published a paper on cometary calculations.[9] He also computed the first orbit of Hyperion, the satellite of Saturn discovered by the Bonds. He propounded a method of mechanical quadratures,[10] later more fully developed by Encke. He was also the author of a paper on the use of equivalent factors in the method of least squares.[11]

The reduction of the longitude observations made for the United States Coast Survey by exchange of chronometers between Liverpool and Cambridge was carried on largely under his direction. The results furnished the best determinations of American longitudes made before the introduction of the electric method.

Bond planned the first observations of the zones of faint stars situated between the equator and $1^\circ\ 00'$ of north declination, and did some of the early work. He also carried out many able observations and fertile investigations in the photometry of the sun, moon, planets, and stars.

Nowhere was Bond's originality so well shown as in the early experiments in photographic methods, and especially in his almost prophetic appreciation of the possibilities of astronomical advancement by means of photography. Some of the achievements attained later by other investigators would in all proba-

[9] Mem. Amer. Acad., New Series, 3, 97, 1848.
[10] *Ibid.*, 4, 189, 1849.
[11] *Ibid.*, 6, 179, 1856.

bility have been anticipated by him, had he lived to take advantage of the great improvements in the manufacture of the photographic plate, especially in its sensitiveness. The first photograph of a star was made under the direction of the Bonds in 1850. Earlier photographs of the sun and moon had been obtained elsewhere, but the first photographs of the moon to attract much admiration were made at Harvard in 1849 and the years following.

Wet plates were used in all the experiments carried out by Whipple and Black under the direction of the Bonds. The invention and perfection of the dry plate brought an immense advance in photographic methods, making possible exposures of any desired duration; but these improvements came too late for the Bonds.

The following extracts from a letter written by George P. Bond to Hon. William Mitchell, on July 6, 1857, show how clear and complete was his vision of future possibilities:

About seven years since [July 17, 1850] Mr. Whipple obtained daguerreotype impressions from the image of Alpha Lyrae formed in the focus of the great equatorial, and subsequently from Castor, thus establishing a simple, but not uninteresting fact—the possibility of such an achievement. On these occasions a long exposure of one or two minutes was required before the plate was acted upon by the light, and in this interval the irregularities of the Munich clockwork were so large as to destroy the symmetry of the images, while the smaller stars of the second magnitude would not "take" at all.

For some years Mr. Whipple gave his attention to photographs of the moon and Sun, and the stars were left to themselves. But improvements in the art progressed rapidly; the preparations were more sensitive, the artists had acquired more experience. At the same time the principle of the spring-governor had been thoroughly tested, and found to supply a great desideratum in imparting a sidereal motion to the telescope incomparably more uniform than that attained by the Munich mechanism . . . Messrs. Whipple and Black recommenced their trials on other images (taken by the Collodion process) in March of the present year [1857], and they are still in progress . . . The field for experiment is too vast to be at once occupied, even if we were provided with unlimited means. But the results already obtained in the disconnected attempts we have thus far been enabled to make, are of the highest interest, and suggest possibilities

in the future which one can scarcely trust himself to speculate upon. Could another step in advance be taken equal to that gained since 1850, the consequences could not fail of being of incalculable importance in astronomy.

The same object, Alpha Lyrae, which in 1850 required 100^s to impart its image to the plate, and even then imperfectly, is now photographed instantaneously with a symmetrical disc perfectly fit for exact micrometer measurement. We then were confined to a dozen or two of the brightest stars, whereas now we take all that are visible to the naked eye . . .

On a fine night the amount of work which can be accomplished, with an entire exemption from the trouble, vexation and fatigue which seldom fail to attend upon ordinary observations, is astonishing.

The plates once secured, can be laid by for future study by daylight and at leisure . . . As yet, however, we obtain images only from stars to the sixth magnitude, inclusive. To be of essential service to astronomy, it is indispensable that great improvements be yet made, and these, I feel sure, will not be accomplished without a great deal of experimenting . . . But could we but press this matter on, we should soon be able to say what we can and what we cannot accomplish in stellar photography—the latter limits we certainly have not reached as yet . . . There is nothing then so extravagant in predicting a future application of photography to stellar astronomy on a most magnificent scale . . .

What more admirable method can be imagined for the study of the orbits of the fixed stars, and for resolving the problem of their annual parallax than this would be if we could obtain the impressions of the telescopic stars to the tenth magnitude! . . . It would be useless for me to attempt to describe in a letter the processes and results in detail.

P. S. I find I have forgotten to allude to two important features in stellar photography—one is that the intensity and size of the images taken in connection with the length of time during which the plate has been exposed measures the relative magnitude of the Stars. The other point is, that the measurements of distances and angles of position of the double stars from the plates, we have ascertained by many trials on our earliest impressions, to be as exact as the best micrometric work. Our subsequent pictures are much more perfect, and should do better still.

This letter deals only with the possibilities of stellar photography. Bond, however, was equally interested in the subject as related to the sun, moon, and other celestial objects. Holden calls George P. Bond "the father of celestial photography." The appellation appears just—could the life of Bond have been

spared for 20 or 30 years, he would doubtless have taken a dominant part in the tremendous advances made in astronomical photography through the introduction of the extremely sensitive dry plate.

Bond saw clearly the desirability of seeking a more satisfactory site for the observational part of the observatory work. The atmospheric conditions for refined observations were never good at Cambridge, and have steadily deteriorated owing to the encroachments of a large city. In a letter to J. Ingersoll Bowditch, dated March 31, 1860, he presented the arguments for such a plan, which for lack of funds was not possible of execution during his lifetime. He wrote:

> It would be certain to repay the outlay if an astronomer of experience, furnished with a good telescope and photographic apparatus, should visit different parts of the world (high table-lands and mountains), and experiment on the advantages of a pure and tranquil atmosphere . . . Why should we always have to wait for the example of the governments of Europe in encouragement of scientific enterprises? If our observatory had possessed the means, we should have sent off an expedition of this kind years ago; it was actually proposed, but, of course, nothing could be accomplished without money.[12]

He even suggested that such an expedition should visit California and the west coast of South America, a remarkable proposal in view of what was really done a generation later.

Bond made two trips to Europe, during which he met nearly all the prominent European astronomers, and was everywhere received with distinction.

In 1856, Bond was offered the position of Chief Astronomer of the survey of the northwest boundary between the United States and British Columbia. The salary was about double that which he was receiving at Cambridge, and the position would have brought him distinction. His love of the work at Cambridge, however, and especially the condition of his father's health, induced him to decline the appointment.

Bond was a member of the American Academy of Arts and Sciences, a corresponding member of the Royal Bavarian

[12] Holden, *op. cit.*, 182, 1897.

Academy of Sciences, and a Foreign Associate of the Royal Astronomical Society of Great Britain. As already stated he was the first American to receive the gold medal of the last-named Society. He was not chosen one of the original members of the National Academy of Sciences, incorporated in 1863. This was believed by his friends, probably justly, to have been due to the enmity of the prominent men of science to whom reference has already been made.

Bond died at less than forty years of age. If we take into consideration his continual struggle with financial difficulties, and, during his later years, with consumption, together with the irritation caused by the enmity of the small clique of scientists referred to above, the indomitable energy and devotion which he displayed were heroic, and his achievements memorable.

CHAPTER XVII

WINLOCK AND PICKERING

WITH the passing of the Bonds, a new era was approaching. The brief directorship of Winlock may be regarded as transitional. With Pickering came a period of immense development, and the introduction on a large scale of astrophysical problems.

Joseph Winlock, 1826 to 1875; Director, 1866 to 1875.— Joseph Winlock, third director of the Observatory, was born in Shelby County, Kentucky, on February 6, 1826. It may be of interest to note that the preceding director, George P. Bond, was born in 1825, and the distinguished American astronomer Benjamin A. Gould, in 1824.

Mr. Winlock came of a notable family. His grandfather, Joseph Winlock, by birth a Virginian, was an officer of the American Revolution who served under Washington and attained the rank of captain. Later he married Miss Stephenson of Virginia, and they settled in Kentucky before it became a state. In the war of 1812 he attained the rank of brigadier general. His son, Fielding Winlock, father of the astronomer Joseph Winlock, was a lawyer, and received a part of his legal training in the office of Henry Clay. Fielding Winlock served with his father in the War of 1812 and later held various positions of honor.

Joseph Winlock was graduated from Shelby College in 1845. His unusual mathematical ability must have been evident during his undergraduate career, since at graduation he was appointed Professor of Mathematics and Astronomy in that institution. The opportunities for the study of astronomy at Shelby College must have been limited, but his devotion

to the science was shown by the use of his first savings to purchase a set of the Astronomische Nachrichten. Fortunately for Winlock and for astronomy, the fifth meeting of the American Association for the Advancement of Science (founded in 1847) was held in Cincinnati in May, 1851. Winlock was present at the meeting, and met Benjamin Peirce, Perkins Professor of Mathematics and Astronomy at Harvard University. At this time Peirce was the most famous American mathematician, and his abstruse mathematical treatises were familiar to Winlock.

As a result of his acquaintance with Peirce, Winlock went to Cambridge in the following year, 1852, to take part in the work of the newly established office of the American Ephemeris and Nautical Almanac. This department had been authorized by act of Congress in 1849. It was placed under the superintendency of a naval officer, Lieutenant C. H. Davis, but the responsibility for all the mathematical formulae and computations was intrusted to Professor Peirce. On this account, and in order to make use of the library and other advantages of Harvard University, the headquarters of the Ephemeris were located in Cambridge until they were removed to Washington in 1866. The first volume of the Ephemeris, for 1855, was issued in 1852.

On his arrival in Cambridge, Winlock joined the able corps of computers attached to this service, which successfully established the reputation of the American Ephemeris under the direction of Professor Peirce. Among these computers were Simon Newcomb, Truman H. Safford, John D. Runkle, William Ferrel, Maria Mitchell, and others well known in later years.

Winlock remained in Cambridge until 1857, when he was appointed Professor of Mathematics in the United States Naval Observatory at Washington. He resigned this position soon after to accept the superintendency of the American Ephemeris and Nautical Almanac, and returned to Cambridge. His name appears as Superintendent in the volumes of the

Ephemeris for the years 1860 and 1861, published in 1858 and 1859. In 1859, Professor Winlock was chosen to take charge of the mathematical department of the United States Naval Academy, and moved to Annapolis. The Naval Academy was later removed to Newport, on account of the Civil War, and at that time Mr. Winlock was again made Superintendent of the American Ephemeris, and returned to Cambridge. His name again appears as Superintendent in the volumes for the years 1864 to 1867, published during the years 1862 to 1865.

Until his appointment as director of the Harvard Observatory, Winlock had devoted his life chiefly to the study, teaching, and development of mathematics. His chief acquaintance with astronomical instruments appears to have been with an excellent telescope of 7½ inches aperture, the property of Shelby College. When he was appointed an assistant at the Cambridge office of the American Ephemeris and Nautical Almanac, Winlock borrowed the telescope from his old college and had it mounted in Cambridge.

In the University of Missouri Catalogue for 1884 to 1885, the following description of the Shelby telescope is given:

This telescope was ordered in 1848 from the establishment of Merz & Mahler,[1] of Munich, for the use of Shelby College, Shelbyville, Kentucky. It was received at Shelbyville in November, 1850, and cost, when mounted, $4,000. It was mounted under the direction of Prof. Joseph Winlock, and used by him when he was a professor in that institution. After Prof. Winlock went to Cambridge, Mass., he borrowed this telescope, and, in connection with Dr. B. A. Gould, established there the Cloverdon Observatory. In Loomis's *Recent Progress of Astronomy*, the following statement is made respecting this instrument, which was then the fourth in magnitude in the United States:

"The great telescope belonging to Shelby College was loaned to Prof. Joseph Winlock, and was removed to Cambridge, Massachusetts, where temporary accommodations were provided for it, and this establishment is known by the name of Cloverdon Observatory." . . . "Numerous observations on comets, and on some of the newly-discovered planets,

[1] In the Report of the Director of the Laws Observatory, March, 1903, Seares pointed out that the telescope bears the inscription: "Merz u. Söhne in München."

have been made with this telescope by Dr. B. A. Gould and Prof. Joseph Winlock, some of which have been published in *Gould's Astronomical Journal.* This great telescope has recently been returned to Shelby College."

It is of interest that this was also the first instrument ever used by Dr. Harlow Shapley, the present Director of the Harvard Observatory. The telescope was purchased by the University of Missouri, and installed as the principal equipment of the Laws Observatory.

In February 1866, without any solicitation on his part, Winlock was chosen Director of the Astronomical Observatory of Harvard College, and at the same time was made Phillips Professor of Astronomy. Later he was also given the title of Professor of Geodesy.

On assuming the directorship he evinced a rare talent in mechanical construction and invention. During the nine years of his supervision he devoted himself with enthusiasm not only to the improvement of the existing equipment, but also to the acquisition of new instruments.

The large 15-inch refractor, the glory of the early days of the Observatory, no longer played the rôle which it held under the Bonds. Under those able observers it had brought much prestige to the institution, but the age of great discoveries by visual means was passing. Under the direction of Winlock, the telescope was used chiefly for observations of double stars. A large number of miscellaneous spectroscopic observations of stars, nebulae, and comets were also made. Of special interest was a spectroscopic research on the aurora, by C. S. Peirce. The instrument was also used by N. S. Shaler, E. L. Trouvelot, and others, for special studies.

Under the Bonds, the large refractor had been used in part for the determination of the positions of stars, especially in the zone between declination $0°0'$ and $+1°0'$. Mr. Winlock decided to discontinue the use of the large equatorial for such observations, and to employ a new and larger meridian instrument.

The meridian circle already in use had never been satisfactory for the determination of declinations. Winlock impressed upon the friends of the Observatory the need of a new meridian circle, and twelve thousand dollars were promptly subscribed for this purpose. The director then spent four months in Europe visiting the principal observatories, and making himself familiar with the latest improvements in meridian instruments. In the new instrument, made by Troughton and Simms of London, were incorporated certain improvements suggested by Mr. Winlock, as described in Chapter IV. Observations were begun with this instrument in 1871. It was used for many years in work on the positions of stars, at first by Professor W. A. Rogers and later by Professor Arthur Searle.

Winlock took part in two expeditions to observe total eclipses of the sun. In 1869, he was requested by Professor Peirce, at that time Superintendent of the United States Coast Survey, to go to Kentucky at the head of a party whose duty it should be to cooperate with officers of the Survey in the observation of the total solar eclipse of August 7. Mr. Winlock gave special attention to spectroscopic and photographic observations, then in their infancy. Several new and effective mechanical devices were introduced by him.

Winlock also had charge of the party sent to Spain to observe the eclipse of December 22, 1870. He prepared for this expedition a lens of 32½ feet focal length, mounted in a horizontal position. The image of the sun was thrown upon the lens by means of a heliostat. By this device the necessity of using an enlarging lens was avoided. The success of these observations and the convenience of the method caused its wide adoption by other astronomers. Beginning in July, 1870, similar apparatus was in use for some time at the Harvard Observatory for daily observations of the solar surface.

During Winlock's administration the time service was much improved and extended. The regular transmission of time signals to Boston was begun in 1872, and the service was made to yield a moderate financial return. The installation and

maintenance of this service, however, was a severe tax on the time and energy of the small staff of the Observatory.

Winlock took a loyal and unselfish interest in the unpublished work of his predecessors. A considerable part of his time was spent in the reduction and preparation for the printer of the unpublished observations made during the administration of the Bonds.

Professor Winlock's personal characteristics were such as to command not only the respect but also the affection of those with whom he was intimately associated. Among strangers he was singularly reticent, and even with his friends his words were often as brief as circumstances permitted. He had, however, a quiet sense of humor.

Newcomb, in his Reminiscences, relates the following story, which in a slightly different form was current at the Observatory. Mr. Winlock was introduced to a lady. They regarded each other for a decorous interval, but neither said a word. Later Mr. Winlock was asked, "Why did you not talk to the lady?" He replied, "I had no statement to make to her."

Mr. Hilgard, when in charge of the Coast Survey, was impressed by the terseness of the communications he received from Mr. Winlock and resolved to rival them. A child had been born in the family of each. Hilgard addressed a communication to Winlock in these words: "Mine's a boy. What's yours?" The reply was: "Dear Hilgard;—Boy. Yours, etc. J. Winlock."

Among friends Mr. Winlock was genial and, on rare occasions, even talkative. In his administrative capacity, which was tested in various positions during his life, Winlock displayed to his associates and assistants unusual disinterestedness, keen appreciation, and a delightfully serene nature.

His leadership was nowhere asserted but everywhere acknowledged. A man of few words but of much thought, of no pretensions but of great performance, he did his own part patiently and well, and by his example inspired others to do theirs.

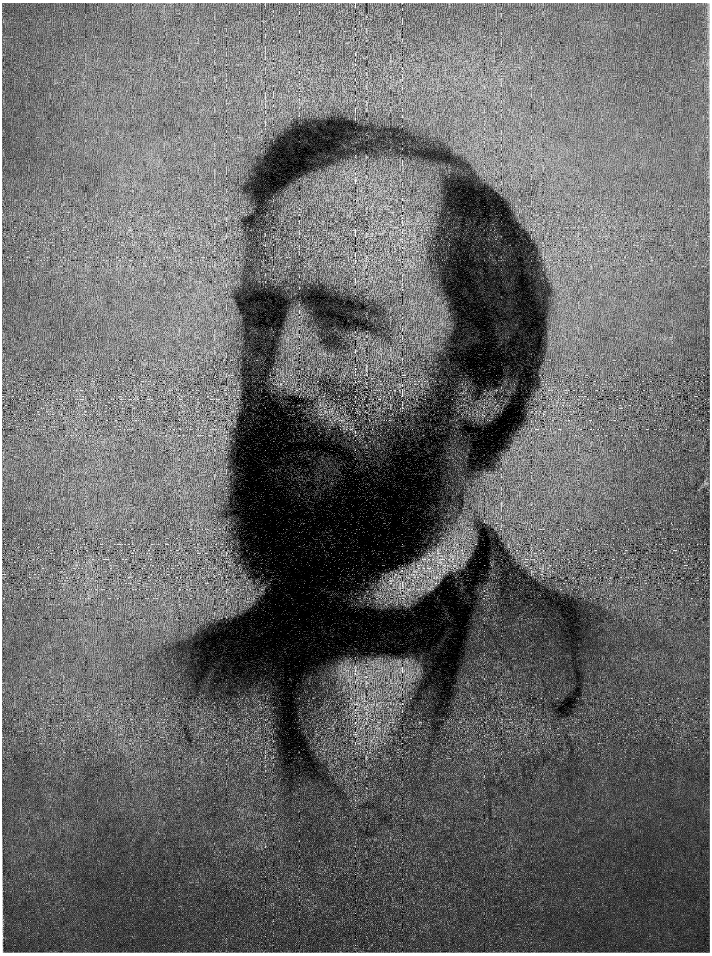

PLATE XXI.—JOSEPH WINLOCK.

(Facing page 242)

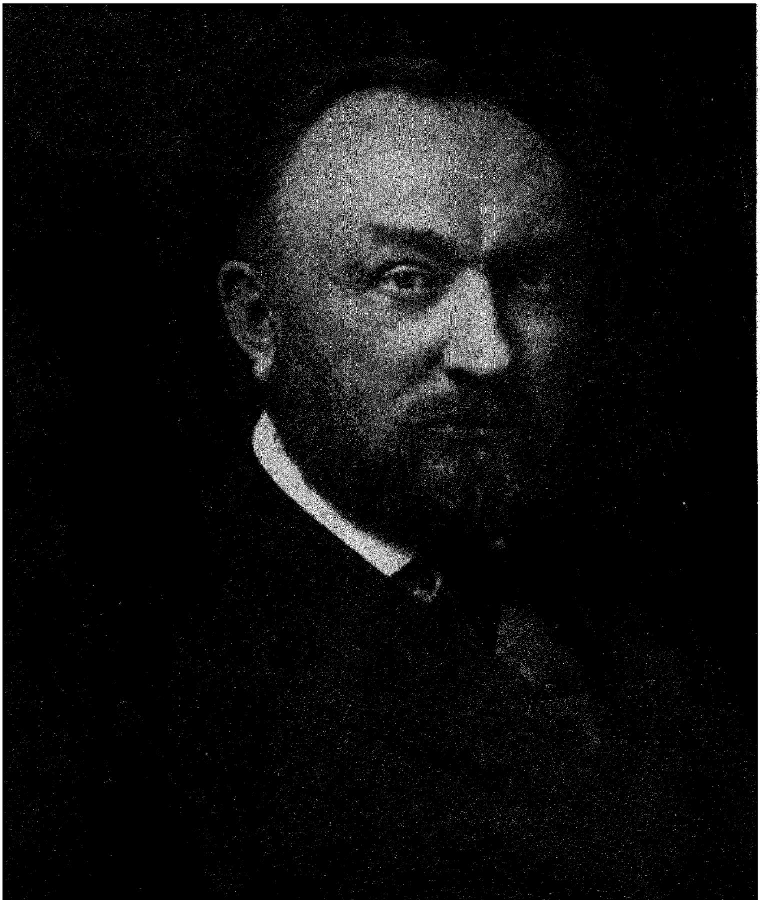

PLATE XXII.—EDWARD C. PICKERING.

Professor Winlock's work as director was chiefly administrative. His own observations were comparatively few, but much was accomplished under his direction. He wrote almost as sparingly as he spoke. No one questioned, however, his thorough knowledge of all the technicalities and principles involved in the different instruments and investigations. His brief directorship was largely absorbed in a disinterested effort to perfect and increase the equipment of the Observatory. In addition to the new large meridian circle, to which reference has already been made, many other new instruments were acquired. These included a Clark refractor, clocks and chronometers, a Russian Transit made in the workshop of the Poulkova Observatory, a Zöllner astrophotometer, and various spectroscopes and meteorological instruments.

In the midst of such activities, when the material equipment of the Observatory had been brought to a satisfactory condition and a long period of useful service seemed to open to him, Winlock died suddenly and unexpectedly at the age of forty nine years.

Edward Charles Pickering, 1846 to 1919; Director, 1877 to 1919.—Edward Charles Pickering was born on Beacon Hill, Boston, July 19, 1846. He died at Cambridge on February 3, 1919. At the time of his death the Observatory was less than eighty years old, and he had been Director 42 years, a period considerably longer than the combined terms of his three predecessors.

Mr. Pickering was fortunate in his heritage. Of a family always prominent in New England history, he was heir neither to riches nor poverty, but to splendid opportunity, which he eagerly grasped. From early youth to old age, his zeal in the pursuit of scientific problems was unbounded. His education was begun in private schools, but later carried forward at the Boston Latin School. He had small love of the classics and gave them scant attention. In the Lawrence Scientific School, however, he entered upon his work with that enthusiasm which

marked all the activities of his mature life. He was graduated from this school *summa cum laude* at the age of nineteen, and was immediately appointed Instructor in Mathematics in that institution. A year later he became Assistant in Physics at the Massachusetts Institute of Technology, and in the following year Thayer Professor of Physics, a position which he held until be became Director of the Observatory. During his ten years at the Institute, the history of his work is the history of the Department of Physics. His appointment as Thayer Professor came at the urgent request of President William B. Rogers, the former occupant of the chair, who wrote to Pickering regarding it:

> Let me say that, with all the urgency of other Institute duties, I should be quite unwilling to relinquish it to any other successor, so much do I love its exercises, and so sure am I that under your direction they will preserve the breadth and practical character which it has been my aim to give them.

At this time Pickering was only twenty two years of age. During the busy years of his professorhip at the Institute, 41 scientific papers were published by him (or by students under his direction) as well as two volumes of his pioneer textbook entitled Physical Manipulations. He established in connection with these volumes the first physical laboratory in America for students. The idea of such a laboratory had been suggested by President Rogers but its successful installation and management were due to Pickering. The importance of this development was widely recognized; it has been regarded as marking an epoch in the teaching of physics. Pickering measured the value of the course in physical manipulation by its success in teaching the student to think for himself, and in fitting him to solve problems experimentally. Research was Pickering's chief interest, although teaching consumed the greater part of his time. His own investigations, on the subject of light, formed a fitting foundation for his future life work.

In 1869 and 1870, Mr. Pickering took part in the expeditions sent out by the United States Government to observe the total

solar eclipses. He introduced at the Institute a course of lectures for older students on geodesy and topography, and one on practical astronomy, especially for engineers. He also designed a spectrometer, which was constructed by Alvan Clark and Sons, and was the most powerful instrument of its kind at that time.

A notable contribution of a different character was made by his early experiments with the telephone. In 1870 he constructed a receiver consisting of a flexible iron diaphragm supported at the edges and replacing the armature of an electromagnet. The apparatus appears to differ in no way in principle from the receiver later in use. He would not consider protecting the device by patent, since such a course would have been contrary to his code of ethics.

In 1876 Pickering founded and became first president of the Appalachian Mountain Club. The great value of this club for popular purposes is well known, but his primary aim was the furthering of health and science. He perfected a portable 12-pound micrometer level for the rapid determination of approximate positions and altitudes. With this instrument he made thousands of observations of various points of interest in the White Mountains. The intensity of his interest and the enthusiasm and success with which he carried out his plans made a deep impression on his associates.

Professor Pickering was chosen Director of the Harvard Observatory in 1876, and entered upon his duties on February 1, 1877. The appointment of a physicist to direct an astronomical observatory caused some criticism from astronomers of the old school. There was no lack of candidates for the position among astronomers of experience and reputation. President Eliot, however, who called him to the directorship of the Observatory, was thoroughly familiar with the unusual scientific and administrative ability which Pickering had shown at the Massachusetts Institute of Technology.

Pickering found the times propitious for the introduction of new methods. The old astronomy of position and motion

which had occupied the chief place in the programs of the great observatories in the past was destined soon to be pushed into the background by the urgency of astrophysical problems. Even the determination of magnitudes of stars had not been placed on a sound scientific basis, and comparatively little was known as to their nature. Everywhere there was a great dearth of facts. In such a condition of the science, Pickering decided that the accumulation of great masses of data would constitute the greatest contribution he could make to the advancement of astronomy. Theories in regard to the structure of the stellar universe could wisely be deferred until better foundations were provided.

At first the range of his researches was sharply limited by the equipment and resources of the Observatory. There were two instruments of great power and high quality for that day, the 15-inch refractor and the 8-inch meridian circle. The financial resources were insufficient to keep these actively employed and to publish the results. Pickering's first care was to secure additional funds for this purpose and also for the extension of his investigations into new fields. His first Annual Report contained an appeal for financial aid, and every succeeding report included some such direct or indirect appeal. The great schemes he was planning could be carried out only through the assistance of many minds and many hands, and these could be obtained only by a great increase of endowment. Little by little this was secured. His own part in this increase was considerable. In all, he gave to the Observatory more than a hundred thousand dollars.

The first and one of the greatest of his achievements was in stellar photometry. For a while, for lack of suitable instruments, he carried on investigations with photometers attached to the large refractor. These labors held particular interest because of the measurement, in 1877, of the newly discovered satellites of Mars. While he was engaged in carrying on these investigations, a meridian photometer was constructed for the convenient measurement of the magnitudes of all the brighter stars.

The improvement of the photographic dry plate came at the beginning of Pickering's administration, and its possibilities were promptly grasped by him. Something of romance was perhaps lost by the introduction of photographic methods, but the gain in efficiency was tremendous. Charting a field of stars, formerly a labor of weeks or months, could be accomplished in an hour, the resulting photograph often showing more stars than could be seen by the eye with a telescope of equal size.

Pickering early saw the possibility of photographic photometry and made many experiments and observations. For many years the difficulties were too great for its successful use, but before the close of his life these had been overcome in large part. He conceived the idea that a large collection of celestial photographs, covering the whole sky and repeated at short intervals over a long series of years, would have immense value, and he attempted to make this record of the stars as complete as possible. An auxiliary station was founded in the southern hemisphere in order to cover the whole sky. Photographs of various kinds were taken, especially charts, and the spectra of the stars were obtained with the objective prism. Records were made with instruments of widely different powers: at one extreme the 24-inch Bruce doublet, which, with an exposure of one hour showed stars to about the seventeenth magnitude; and at the other extreme, a wide-angled one-half inch Ross-Zeiss lens covering a field about 60 degrees square, so that the entire sky available could be covered in a single night with exposures of one hour, stars to about the ninth magnitude being photographed.

The extensive discoveries of novae, asteroids, variable stars, and other interesting celestial objects from this collection of photographs are ample proof of its value. A series of plates having exposures of four hours with the 24-inch Bruce was proposed, and a considerable number of excellent photographs were made at Arequipa from the South Pole northward. Such a series, if it could be completed for the whole sky, would

contain a hundred million or more stars, and from it might be derived definitive lists of clusters and nebulae for the determination of their distribution, motions, and distances. The scheme, however, would require a long time for its completion with a single telescope, and meanwhile the Selected Areas of Kapteyn, Pickering's own Standard Regions, and other cooperative plans made this complete plan less necessary.

The study of stellar spectra, carried on by several observers under Pickering's direction, constitutes one of the greatest achievements of the Observatory. The completion of the Henry Draper Catalogue, giving the spectral classification of more than two hundred thousand stars, formed a fitting close to Pickering's career. To estimate its importance, one needs only to remember how small was our knowledge of the nature of the stars in 1885, when he began to photograph them with the objective prism, and to consider how intimately the Harvard classification has entered into nearly all lines of astronomical research.

Aside from the classification of spectra, the objective prism plates yielded enough in the way of by-products to justify Pickering's enthusiasm: several novae, hundreds of new variable stars, and long lists of peculiar stars of special interest. Nothing pleased him more than to know that the results obtained at the Observatory were those most needed by astronomers in their investigations. Certainly no better example could be found of a recognized and fulfilled astronomical need than the classification of stellar spectra in the nine volumes of the Henry Draper Catalogue, as carried out by Miss Cannon.

His conception of a vast collection of photographs of the stars, destined in time to give a history of the sky, was unique. Its execution was carried forward with zeal and success. These half-examined plates, made, in many cases, only for the purpose of securing as complete a record as possible, appeared to many as unnecessary and extravagant, and even excited ridicule. This seems absurd now that their value has been so fully demonstrated. Hardly a new star or variable has been

discovered in recent years whose history could not be traced in a large degree upon these photographs. The study of the minor planet Eros as described in Chapter VII furnished an early example of their value. Although so long in use, this collection still exists, growing more valuable with lapse of time. Constant additions are being made to it under the direction of Dr. Shapley.

It is possible that Pickering's best work was in photometry and spectroscopy, but he was active in many other fields. The study of variable stars was a marked feature of the Observatory work during his administration. When he began his observations, about 200 variables were known; at the time of his death, 3435 variables had been found at the Harvard Observatory. He published, in 1880, a classification of variable stars which is the accepted notation at the present time. He soon began to encourage their observation on a scale hitherto unknown. This was possible not only through the increasing resources of the Observatory, but also through the assistance of amateurs. When the American Association of Variable Star Observers was formed, he gave the members the assistance which they needed. The spirit in which this was given and received is well shown by the regard and affection in which he was held by the members of the Association. At their meeting in 1918, they presented him with a beautiful gift, after their president had made the following reference to him: He has assisted us in everything that we have undertaken and has carefully watched our progress along every step of the way, and the manner of his so doing has been that of the Big Brother.

The astronomy of position was not neglected during Pickering's directorship, although his chief interests lay in astrophysical lines. Two zones of the Astronomische Gesellschaft, those from $+49° \, 55'$ to $+55° \, 10'$, and from $-9° \, 50'$ to $-14° \, 10'$ declination, were observed and published during that time, although the observations for the former zone were begun under Professor Winlock. Altogether, the work of the meridian circle occupied the time of one professor and several assistants

during half a century, the results filling a dozen volumes of the Annals.

When Pickering came to the Observatory, only a dozen volumes of the Annals had been published or were ready for printing. At the time of his death, about 80 of these quarto volumes had been issued or were practically ready for the printer. Many of these, indeed, were chiefly the work of others, supervised or edited by him. On the other hand, an enormous amount was his own. He was a natural leader, but he was an indefatigable worker as well. He worked for the real love of it, carrying on observations for several hours each clear night, in addition to his arduous duties as director. Of the two million observations concerned in the visual Harvard Photometry, more than half were made by him.

Pickering's interest in the work of others seemed as intense as that in his own. His desire was to secure the largest possible results. If he was fond of quantity, the care with which he examined and reexamined all that he did is evidence that quantity was not sought at the expense of quality. Loyalty to his predecessors in office was one of his marked characteristics. He devoted much time and badly needed financial resources, during the early years of his directorship, toward completing and publishing their unfinished work.

As unusual as were Pickering's scientific accomplishments, his personal qualifications were equally rare. For men and women he had an equal charm. His grace of manner and conversation captivated all those who knew him intimately. To all who seemed to have any claim upon him, he gave a courteous regard. He seemed always able to draw out a person's best qualities, and to leave him with the rare and happy sense of having found at last real appreciation. To astronomers especially he was ready with unlimited service, and he is remembered by many as an ideal host.

Pickering thoroughly believed in the advantage of broad associations for the good of science and mankind. One of the most cherished objects of his life was to secure an international

fund for the benefit of astronomers of all nations. Of a similar nature was his plan for an international southern telescope which would be devoted to the needs of astronomers anywhere.

Believing that the best service he could render to astronomy was the accumulation of facts, to this end he massed all the forces he could command, instituting great pieces of research, sometimes employing many routine workers, that in the end a sufficient basis should be provided for a solution of stellar problems. His practical nature led him to adopt graphical instead of analytical methods, whenever they appeared equally accurate.

Pickering loved to discuss but refused to dispute. He loved appreciation, but was not swerved from an approved course by its absence. His persistence in what he believed right was balanced by a readiness to accept new ideas. Until the very end of his life he kept an alert, unprejudiced mind, and was always glad to modify or abandon his plans if something better presented itself. He was prompt to give advice, whenever it was requested, and possibly in some cases where it was not desired. Always glad for friendly suggestions himself, he did not hesitate to offer them to others. He was held in high esteem by his fellow astronomers. The following tribute (1919) is from one of them:

> His wonderful energy and enthusiasn, his alertness, his unvarying courtesy, his wide vision and generous heart, make his passing a keen personal loss even to those of us who knew him slightly. For a number of years I have thought of him as the Dean of American Science.

Mr. Pickering was married in 1874 to Lizzie Wadsworth Sparks, daughter of Jared Sparks, a former President of Harvard University and a well-known historian. Mrs. Pickering, who is still remembered as an especially charming hostess, died in 1906. No children were born to them.

Pickering received nearly all the honors which the world had to bestow on a scientific man. These he valued highly as the expression of the appreciation in which his work was held. He received the honorary degree of Doctor from six

American and two foreign universities. He took special pride in being a Knight of the Ordre Pour la Mérite. His collection of medals was a large one; he was twice awarded the gold medal of the Royal Astronomical Society. In addition to membership in American societies, he was a member or associate of the national societies of England, Germany, Ireland, Italy, Russia, Sweden, and Mexico. He was made a member of the American Academy of Arts and Sciences at the age of twenty one, and a member of the National Academy of Sciences at the age of twenty seven. He was President of the American Astronomical Society from its foundation in 1903 until his death in 1919.

CHAPTER XVIII

LEADING MEMBERS OF THE OBSERVATORY STAFF

MANY individuals have taken part in the investigations of the Observatory, as shown by the list of members of the staff given in Chapter XX. The work of a number of these was of sufficient originality and importance to merit special consideration of the authors. A few are mentioned not especially for the quality of their work as assistants at the Harvard Observatory, but for the scientific eminence which they later attained elsewhere. The Observatory takes pride in their temporary association with it. Sketches are not given here for any member of the staff who was living at the end of 1927.

Charles Wesley Tuttle, 1825? *to* 1881; *Staff Member,* 1850 *to* 1854.—Charles Wesley Tuttle was one of the earliest assistants of the Observatory, under the directorship of W. C. Bond. He took part in the observation of the stars in the zone from the equator to $0° 20'$ north declination. This work was done, according to the title page of Volume **1**, Part 2, of the Annals, by George Phillips Bond, A.M., First Assistant, and Charles Wesley Tuttle, A.M., Second Assistant. Tuttle also took part in the observations of Saturn, under the direction of W. C. Bond, the results of which were published in Volume **2**, Part 1, of the Annals. He resigned his position in the Observatory in 1854, since his eyesight did not permit him to pursue regular observations longer. Later he took up the study of law, but for several years at least he retained his interest in astronomy, computing the orbits of comets. Tuttle received the honorary degree of A.M. from Harvard University in 1854, and Ph.D. from Dartmouth in 1880.

Horace Parnell Tuttle (brother of C. W. Tuttle?), an assistant from 1858 to 1862, was especially devoted to the discovery of

comets and the computation of their orbits. He resigned in 1862 in order to enter the Army. Later he resided in Georgetown, D. C., and in Washington. He received an honorary A.M. from Dartmouth in 1866 and from Harvard in 1868.

Etienne Léopold Trouvelot, 1827 *to* 1895; *Staff Member*, 1872 *to* 1874.—Trouvelot was a Frenchman who resided for many years in the United States, for a time in Medford and later in Cambridge. He was engaged by Professor Winlock to make drawings of various celestial objects during the years 1872 to 1874. He also had a small private observatory in Cambridge. While residing in Medford he began a series of observations of the sun's surface which was greatly extended during his stay at the Harvard Observatory. Nearly a thousand such drawings are in the possession of the Observatory. Trouvelot made beautiful drawings of various other celestial objects, including total eclipses of the sun, the surface of the moon, planets, comets, and nebulae. These drawings show a rare artistic ability. So far as published by the Observatory, they appear in the Annals, Volume **8**, Part 2.

Trouvelot was also interested in physical investigations and in zoology. During some experiments on which he was engaged at Medford, several specimens of the gypsy moth accidentally escaped and caused an immense injury to plant life, a source of deep regret to him. Trouvelot wrote many scientific papers, chiefly on astronomical subjects, which were published in various scientific journals, in France and the United States.

Asaph Hall, 1829 *to* 1907; *Staff Member*, 1857 *to* 1862.—Professor Hall's childhood and early manhood were passed amid the difficulties which accompany poverty. His father died when he was thirteen. Hall was the eldest of six children, and for many years had to assist his mother, who had been left in straitened circumstances. At sixteen he was apprenticed to a carpenter for three years. After he was twenty one he began to save money with which to obtain an education. At twenty five he started a course at Central College, McGrawville,

New York, attracted by the low costs and the opportunity to pay his way by manual labor. He was dissatisfied with the college and remained little more than a year; but he became engaged to Miss Stickney, a pupil and instructor at the college. They were married in Wisconsin in 1856. In the same year he entered the University at Ann Arbor, where he remained only long enough to become familiar with the manipulation of astronomical instruments through the instruction of Brünnow. After a brief experience in teaching he and his wife came to Cambridge and he became an assistant at the Harvard Observatory. His salary at first was $3 a week. Later it was advanced to $400 a year. Hall's spare time was spent in the study of mathematics, astronomy, and languages. As a paid assistant his work at the Observatory was chiefly of a routine nature. In 1862 he received an appointment as Aide at the U. S. Naval Observatory, and, in 1863 became Professor of Mathematics in the Navy. His greatest achievement perhaps was the discovery of the two moons of Mars.

Professor Hall was an assiduous observer, a deep student, and a prolific writer. The mere titles of his different papers, problems proposed, and observations made, with the briefest outline of their nature, would fill some thirty pages of the size used in this volume. He received the gold medal of the Royal Astronomical Society, the Lalande prize, the Arago medal of the French Academy of Sciences, and was made a Knight of the Legion of Honor. He was a member of the more important scientific societies, both at home and abroad. He received honorary degrees from many universities, including that of LL.D. from Yale and Harvard. At the legal age of sixty two Hall was retired from his professorship in the Navy; a little later he became a lecturer on celestial mechanics at Harvard University. The last few years of his life were passed at his country home in the town of his birth, Goshen, Connecticut.

William Augustus Rogers, 1832 *to* 1898; *Staff Member*, 1870 *to* 1886.—Professor Rogers was born at Waterford, Connecticut, November 13, 1832, and died at Waterville, Maine,

on March 1, 1898. He graduated from Brown University in 1857, and for the next 13 years passed the greater part of the time at Alfred University as Professor of Mathematics and Astronomy. During this period, however, he spent a year at the Sheffield Scientific School of Yale University as a student of mechanics, and a year at the Harvard Observatory in the study of astronomy under Professor Bond.

He became a regular assistant at the Observatory in 1870, and was soon placed in charge of the new meridian circle by Professor Winlock. His chief work with this instrument was the observation of the zone of stars from 49° 50′ to 55° 10′ north declination.

Rogers became Assistant Professor of Astronomy in 1877, and held that position until he accepted a professorship of Physics and Astronomy at Colby College in 1886.

Rogers was also interested in the standards of length, temperatures, and other physical constants, and wrote many papers on these subjects. He was sent to Europe in 1879 by the American Academy of Arts and Sciences to obtain copies of the imperial yard and the mètre des archives. The copies were widely employed in the United States and Canada.

Rogers was a Fellow of the Royal Society of England, and later an Honorary Fellow of that body; Honorary Fellow of the Royal Microscopic Society; Fellow of the American Association for the Advancement of Science, twice president of Section A, and once of Section B; member of the American Academy of Arts and Sciences, and of the National Academy of Sciences. He received the honorary degrees of A.M., Ph.D., and LL.D. from Yale, Alfred, and Brown Universities, respectively. Rogers took a keen interest in civic and religious activities. A kind and generous nature endeared him to his associates.

Samuel Pierpont Langley, 1834 *to* 1906; *Staff Member*, 1865 *to* 1866.—Langley, one of America's most distinguished men of science, was born in Boston, August 22, 1834, and died in Washington, February 27, 1906. He was graduated from the Boston High School in 1851, and took up the study of

engineering and architecture which he followed until 1864. In that year and the following he travelled in Europe visiting the principal observatories. On his return in 1865, he became an assistant in the Harvard Observatory, remaining until he received, in 1866, an appointment as Assistant Professor of Mathematics at the United States Naval Observatory. Subsequently he became Director of the Allegheny Observatory, where he remained 20 years. Langley was a remarkable observer, as is shown by his drawings of the sun's surface and of various other celestial phenomena. He devised the bolometer for a detailed study of the intensity of the radiations from different parts of the solar spectrum, and from other bodies.

In 1887, Langley became Secretary of the Smithsonian Institution, where he founded the Smithsonian Astrophysical Observatory and carried on a long series of bolometric determinations.

Langley was a pioneer in aerodynamics, and was almost the first to make a heavier-than-air machine which could fly. He was the author of many scientific papers, and his achievements met with wide recognition. He received the degree D.C.L. from Oxford, and D.Sc. from Cambridge, England; Ph.D. from Stevens Institute of Technology, and LL.D. from several American universities. He never married.

Truman Henry Safford, 1836 *to* 1901; *Staff Member,* 1854 *to* 1865.—Professor Safford was graduated from Harvard College with special honors at the age of eighteen, and worked for a time in the Cambridge office of the American Ephemeris and Nautical Almanac. Newcomb, in his Reminiscences, refers to him as "the most wonderful genius in the office, and the one who would have made the most interesting subject of study to a psychologist." Safford was, in his youth, and indeed throughout his life, what is known as a "lightning calculator." He himself was reticent as to this unusual endowment, but his reputed ability in this line was marvellous. While at the Harvard Observatory, he accomplished a large amount of valua-

ble work, chiefly in the astronomy of position. He took a prominent part in the observation and reduction of the zones of faint stars observed near the equator with the 15-inch telescope, and of meridian circle observations. The results are contained in the Annals, **2**, Part 2; **4**; and **6**. He also assisted Professor G. P. Bond in the determination of the positions of stars in the Great Orion Nebula and after Bond's death carried out the publication of his observations, as given in Volume **5** of the Annals. He was in charge of the Observatory for several months after the death of Bond, until the appointment of Winlock as director.

Safford was chosen Professor of Astronomy in the old University of Chicago in 1865, and Director of the Dearborn Observatory. In 1876, he became Field Memorial Professor of Astronomy at Williams College, where he remained until his death in 1901.

Arthur Searle, 1837 *to* 1920; *Staff Member*, 1868 *to* 1920.— Professor Searle was born in London, October 21, 1837. His mother was of English birth, but his father, though living in England, was of New England ancestry, a descendant of Thomas Dudley, second Governor of Massachusetts.

Searle was graduated from Harvard College in 1856, the second scholar in his class. For twelve years he engaged in a variety of pursuits, until in 1868 he was offered a position as assistant at the Harvard Observatory. Although he accepted the position in a tentative way, he soon became so interested in his work that he remained in the Observatory until his death, a period of over 52 years, by far the longest term of service of any member of the staff. For 44 years he was in active service, and for the last eight years, as Professor Emeritus, he still carried on some astronomical work.

Searle received a formal appointment in 1869, was made Assistant Professor in 1883, and Phillips Professor of Astronomy in 1887. From the death of Winlock in 1875 until Pickering assumed the directorship in 1877, Searle performed the duties of acting director, and spent much of his time in preparing for

publication the observations already made. He also wrote a history of the Observatory from the close of Professor Bond's history, given in Volume 1 of the Annals, until the year 1876; it is published in Volume **8** of the Annals.

Searle's chief work was the study of the zodiacal light and, especially, the observation of the zone of stars from $9^\circ\ 50'$ to $14^\circ\ 10'$, south declination. He also took a large part in the early observations of the Harvard Photometry. He wrote many articles for scientific and popular journals, as well as a textbook on astronomy.

Searle was a man of unusually broad culture. Although he made a successful career as an astronomer, he had no special desire in his youth to become one. He would probably have made an equal success as a mathematician, a linguist, a philosopher, or a teacher. As a diversion he wrote verse both in Latin and English, some of which appears to show real poetic spirit. He also wrote on mathematical and philosophical subjects.

Professor Searle was singularly unassuming. With talents which, with strong ambition, might have carried him to almost any position in the scholarly or scientific world, he was content to allow his life to flow on quietly; a strenuous life had no appeal to him. Quiet and retiring, with an appearance almost of gruffness, he yet showed himself, once his attention was attracted, as one of the most genial and lovable of men.

George Mary Searle, 1839 *to* 1918; *Staff Member,* 1866 *to* 1868.—George M. Searle, brother of Professor Arthur Searle, was born in London, June 27, 1839, and died in Washington, July 7, 1918. He was graduated from Harvard College in 1857, and was given the honorary degree of Ph.D. by the Catholic University of Washington in 1896. He was an assistant at the Dudley Observatory, 1858 to 1859; with the Coast Survey, 1859 to 1862; Assistant Professor at the United States Naval Academy, 1862 to 1864; and assistant at the Harvard Observatory, 1866 to 1868.

He adopted the Roman Catholic faith in 1862, and left the Harvard Observatory in 1868 to become a member of the

Paulist Order. The remainder of his life was passed as a member of that Order; he carried on some astronomical work and was for a time Professor of Mathematics in the Catholic University of Washington. For many years Father Searle was Superior General of the Paulist Order in the United States. He was the author of several books and pamphlets. In 1916 he retired to the Apostolic Mission House, Washington.

Charles Sanders Peirce, 1839 *to* 1914; *Staff Member,* 1868 *to* 1875.—Mr. Peirce, son of the celebrated mathematician Benjamin Peirce, was born in Cambridge, Massachusetts, September 10, 1839, and died in Milford, Pennsylvania, April 19, 1914. A man of brilliant attainments in several fields, he applied his energies at different times to mathematics, philosophy, logic, astronomy, and other branches of science. During the latter part of his varied career, he lived in retirement at Milford.

Peirce acted as assistant at the Observatory under Professor Winlock, in 1868 and 1869, and later during the years 1872 to 1875. In the latter period, he was really an assistant of the United States Coast Survey, but was directed by the Superintendent in 1871 to report to Winlock for duty as assistant at the Harvard Observatory. An arrangement was made by which a Zöllner astrophotometer was obtained and Peirce carried out during the next three years photometric observations of 494 stars in declination $+40°$ to $+50°$. He also carried out a discussion of the brightness of the stars as observed by Ptolemy, Sûfi, Argelander, Heis, and others. The results are given in Volume 9 of the Annals.

Peirce was a member of the National Academy of Sciences and a Fellow of the American Academy of Arts and Sciences. He was the author of many memoirs and articles on a wide variety of subjects. He was a contributor to the Century Dictionary and to various encyclopaedias. Peirce had one of the keenest minds which have appeared in American history, but his later life was somewhat clouded by the eccentricities of genius.

Oliver Clinton Wendell, 1845 *to* 1912; *Staff Member*, 1879 *to* 1912.—Professor Wendell was born at Dover, New Hampshire, on May 7, 1845. He was graduated from Bates College in 1868. From this college, also, he received the degree of M.A. in 1871, and of D.Sc. in 1907. He was made Assistant Professor of Astronomy at the Harvard Observatory in 1898.

Soon after graduation in 1868, Wendell became a student at the Harvard Observatory under Winlock, but was compelled to give up this work within a year on account of illness. For about ten years he found it necessary to engage in out-of-door pursuits, but he returned to the Harvard Observatory in 1879, remaining there until his death in 1912.

His work at the Observatory was done in large part with the 15-inch refractor. During the latter part of his life he was almost the only observer with this telescope, and his rèlation with it was in the nature of an intimate friendship. The early glamour of the "Great Telescope" never lost its hold upon him. His work was chiefly in photometric lines. He assisted in carrying out a long series of observations of the eclipses of Jupiter's satellites, and he was especially interested in comets and in the computation of their orbits. His work is published in the Annals, in volumes **13**, **23**, **24**, **33**, **37**, **52**, and **69**.

He was married in 1870 to Sarah Butler, who died in 1910. Two sons survived them.

John Rayner Edmands, 1850 *to* 1910; *Staff Member*, 1880 *to* 1910.—Mr. Edmands became an assistant at the Observatory in 1880, although his name first appears in the official list of the staff, as published in the University Catalogue, in 1883. His work at the Observatory was chiefly in connection with the time service into which he introduced several ingenious improvements. He also served as Librarian of the Phillips Library for many years. His position was that of a volunteer assistant, more than that of a paid employee.

Edmands was a graduate of the Massachusetts Institute of Technology, class of 1869. His chief interests in life, aside from the work at the Observatory, were connected with the

Appalachian Mountain Club, in which as councillor of topography his training as a mechanical engineer rendered him especially efficient. At different times he occupied all the offices of the club, including that of President. He gave time, energy, and money freely to the construction of mountain paths, some of which in his honor have become known as the "Edmands Trails."

Mr. Edmands was born in Boston in 1850, and died in Baltimore in 1910.

Winslow Upton, 1853 *to* 1914; *Staff Member*, 1877 *to* 1879.—Professor Upton was born in Salem, Massachusetts, October 12, 1853, and died in Providence, Rhode Island, on January 8, 1914. He received the degree of A.B. from Brown University in 1875, and was given the honorary degree of Sc.D. by the same institution in 1906. From 1875 to 1877 he was student assistant at the Mitchel Observatory of the University of Cincinnati, receiving there the degree of A.M.

Upton's life was full of incident. From 1877 to 1879 he was assistant at the Harvard Observatory, under the direction of Professor Pickering. In 1879 to 1880 he was assistant engineer in the United States Lake Survey; in 1880 to 1881, computer in the Naval Observatory; and from 1881 to 1883, computer and Assistant Professor of Meteorology in the United States Signal Service. He was appointed Professor of Astronomy at Brown University in 1883, and remained in this position until his death in 1914. Also, he was director of the Ladd Observatory from its foundation in 1891. For many years he was Dean of Brown University.

Upton took part in six expeditions to observe total eclipses of the sun and passed the year 1896 to 1897 at Arequipa, where he determined accurately the position of the southern station of the Harvard Observatory.

While an assistant at the Harvard Observatory in Cambridge, Upton took part in the photometric observations carried on with the large refractor during 1877 to 1879, the results of which are given in Volume 11 of the Annals. As Secretary of the

New England Meteorological Society, he also supervised the publication of the observations by the members of that Society, contained in Volume **21** of the Annals.

Professor Upton was an accomplished musician and also a humorist; while at the Harvard Observatory he wrote a skit entitled "The Observatory Pinafore," which was much admired for its bright and friendly satire.[1]

Williamina Paton Fleming, 1857 *to* 1911; *Staff Member*, 1881 *to* 1911.—Mrs. Fleming was born in Dundee, Scotland, May 15, 1857, and died in Boston, May 21, 1911. Her maiden name was Paton. In early womanhood she married James O. Fleming with whom she came to the United States and settled in Boston. Soon finding it desirable to support herself, she began work at the Observatory in 1881. At first her duties were of the simplest routine character. As her ability became apparent, she was advanced to an important position. Perhaps her most valuable service was in executive and administrative work. It was a period of rapid development at the Observatory under the direction of Professor Pickering, who was busy with many lines of work, especially the introduction of photographic methods. Mrs. Fleming exercised efficient supervision over a large staff of computers and in addition rendered able assistance in the correction of copy and proof for the published results in the Annals and elsewhere. As the collection of photographs of the sky grew larger, she received the official title of Curator of Astronomical Photographs.

A large part of Mrs. Fleming's scientific work was related to stellar spectra. The director assigned to her the examination of the photographic plates, and also the classification of the spectra of the stars contained in the Draper Catalogue. During the execution of these duties, her active mind led her to many discoveries. Chiefly by means of their characteristic spectra, she discovered ten new stars and more than three hundred variables. She also made extended lists of gaseous nebulae and of

[1] This operetta was performed 50 years later by the staff of the Observatory at the meeting of the American Astronomical Society in December 1929.

stars of peculiar spectra. Her principal work is found in the Annals, volumes **18**, **26**, **27**, and **47**, and in various lesser publications.

Mrs. Fleming was an Honorary Member of the Royal Astronomical Society of London, and Honorary Fellow of Wellesley College. She was an active member of the American Astronomical Society, and a recipient of the gold medal of the Sociedad Astronómica de Mexico. Her interests in life were many. She was of an intense and active nature, never idle. She was at the same time scientific and domestic, and had rare skill in the making of small gifts with her own hands. As a descendant of the "fighting Grahams," she was a stern enemy, but a most loyal and faithful friend. She had a magnetic, sympathetic personality, which brought her many devoted friends.

Henrietta Swan Leavitt, 1868 *to* 1921; *Staff Member*, 1902 *to* 1921.—Miss Leavitt was born in Lancaster, Massachusetts, July 4, 1868, and died in Cambridge, December 12, 1921. The daughter of a clergyman, she was of old New England ancestry and inherited in a somewhat chastened form the stern virtues of her forefathers. Her sense of duty was strong, and her devotion to her family, friends, and religion was intense. She was deeply absorbed in her astronomical work, dedicating herself to it with an almost religious zeal.

The scientific results obtained by Miss Leavitt are given in the Annals, **60**, Nos. 2, 4, and 5; **71**, Nos. 3 and 4; **85**, Nos. 1, 7, and 8; and in various Circulars and other publications. Her work was related, for the most part, to the determination of the photographic magnitudes of the stars. Under the direction of Professor Pickering, she carried on with much skill and originality the determination of the magnitudes of a large number of stars near the North Pole, constituting a Standard Sequence of magnitudes. These standards were later extended to the 48 equal areas into which Pickering had divided the sky, and still later, to the Selected Areas of Kapteyn.

In addition to these activities, Miss Leavitt discovered by means of the photographs of the sky in the Harvard collection, four new stars, 2400 variable stars, and several asteroids. She first noted, in connection with her research on the variables in the Magellanic Clouds, the important fact that the length of period bears a definite relation to the absolute magnitude.

CHAPTER XIX

RESEARCH ASSOCIATES OF THE OBSERVATORY

A NUMBER of investigators, some of them eminent men of science, have been temporarily associated with the Observatory in scientific research. In recent times, the great collection of astronomical photographs has proved to be an additional attraction to many, containing as it does an almost inexhaustible supply of fundamental data.

Sydney Coolidge, 1825? *to* 1863.—Coolidge became associated with the Observatory in 1853 and gave to its service a large share of his time and energy for seven years. He took an important part in the chronometer expeditions, at that time the best method of determining the difference in longitude between the Observatory and a European station. For this purpose he crossed the Atlantic several times in the slow ships of the period, having in his care a number of chronometers. He was also active in the observation of the faint stars in the zone near the equator, begun by George P. Bond, but carried forward chiefly by T. H. Safford and himself. Coolidge received the honorary degree of A. M. from Harvard University in 1857. He became a major in the Union Army after leaving the Observatory and was killed in an engagement near Chickamauga, in 1863.

Coolidge's full name was Phillip Sydney Coolidge, but evidently he preferred to have it known as Sydney Coolidge, which, with one or two exceptions, is the name used in the Annual Reports, in various publications, and in the Quinquennial Catalogue of Harvard University.

Seth Carlo Chandler, 1846 *to* 1913.—The name of Seth C. Chandler does not appear in the Harvard Catalogue as an official member of the Observatory staff. He was, however,

connected with the Observatory for many years, chiefly as a volunteer observer and investigator, and was frequently mentioned in the Annual Reports of the Director, from 1880 until the time of his death. He was born in Boston, September 16, 1846, and died in Wellesley Hills, December 31, 1913.

Chandler did not pursue a college education, but was possessed of a keen mathematical mind, and developed a lifelong interest in astronomy. After graduation from the Boston High School in 1861, he became private assistant to Dr. B. A. Gould, thus obtaining his start in astronomy. He became Aide in the United States Coast Survey in 1864. Declining an offer to accompany Dr. Gould to Argentine, he became the actuary of a New York life insurance company, and later accepted a similar position in Boston. He carried on a successful business career throughout life as an actuary, devoting his spare time to astronomy.

One of his earlier accomplishments at the Harvard Observatory was the development of the almucantar and his observations with it. The results are contained in Volume 17 of the Annals. His work on variable stars was of recognized value in the early development of the subject, and his lists of such stars were authoritative as long as they were maintained, until the beginnings of photographic discoveries revolutionized the subject.

Associated with Mr. John Ritchie, Chandler formulated and introduced a convenient code for the telegraphic transmission of astronomical discoveries. He computed the orbits of many comets. He was a brilliant and rapid computer and knew no limit to his time and energy when engaged on an interesting problem. Probably his most remarkable work was the series of masterly papers proving the reality of the variation of latitude.

Mr. Chandler was Editor of the Astronomical Journal from 1896 to 1909; a member of the American Academy of Arts and Sciences, the National Academy of Sciences, and many others. He received the Watson Gold Medal of the

National Academy, and the gold medal of the Royal Astronomical Society. In 1891, he received from De Pauw University the honorary degree of LL.D. Professor Searle said of his work: "His powers of intellect were creative rather than critical; in other words, he has left among those who knew him the remembrance not so much of mere talent as of positive genius."

Abbott Lawrence Rotch, 1861 *to* 1912.—The name of Abbott Lawrence Rotch appears for many years on the staff of the Harvard Astronomical Observatory, as given in the annual catalogue of the University. Rotch, however, was not a salaried employee of the Observatory, but, for greater efficiency in his chosen line of meteorology, he associated himself with the institution by special arrangement with the director, Edward C. Pickering. Rotch was a Bostonian of large wealth and scientific tastes, who, becoming absorbed in meteorological studies, founded in 1885 the Blue Hill Meteorological Observatory as a private institution, maintained and directed by himself. The Annals of the Harvard Observatory contain the chief results of the Blue Hill Observations from 1887 to 1924. It was expected by Professor Pickering and Professor Rotch that both institutions would ultimately be united under one control. At his death in 1912 Rotch bequeathed his observatory to the Corporation of Harvard University, who accepted the gift, but made the Blue Hill Meteorological Observatory a separate department of the University.

For many years Rotch held the appointment of Assistant in Meteorology, but in 1906 he was made Professor of Meteorology in recognition of his service to that science. His position in both cases was honorary, and carried with it no salary. Under his direction, the Blue Hill Observatory achieved a world-wide reputation, for Rotch was a pioneer in the study with kites and sounding balloons of the meteorological conditions in the upper air.

Joel Hastings Metcalf, 1866 *to* 1925.—Dr. Metcalf was born at Meadville, Pennsylvania, January 4, 1866, and died February

4, 1925, at Portland, Maine. In three lines of endeavor he achieved considerable success. First of all he was a preacher, a minister in its best sense, of the Unitarian Church. One of the charming traits of his character was a wide tolerance closely associated with an intense religious faith. He held the degrees of D.D. and Ph.D. and was successful both as pastor and lecturer.

The second absorbing interest in Metcalf's life was astronomy. His passion for this science began in boyhood and lasted throughout his life. As a small boy he made his first telescope with a lens which he worked hard to purchase. During his first pastorate at Burlington, Vermont, he established his first observatory. In 1903, he went to Oxford University for a year's study of theology, but devoted all his spare time to astronomical problems, through the courtesy of Professor Turner. In the following year he accepted a pastorate at Taunton, Massachusetts, and built and equipped a new private observatory. There he first became associated with the Harvard Observatory and a firm friend and admirer of Professor Pickering.

Metcalf not only made astronomical observations of value, but these observations were obtained with telescopes of his own construction. It was in applied optics that his highest scientific work was done. As an expert in this line he probably had no superior. He not only computed his own curves for the lenses, but possessed a genius for bringing them to perfection. Altogether, he ground many lenses. Perhaps the most notable of these was the 16-inch doublet, a photographic instrument which has been in use at the Harvard Observatory for many years. At the time of his death he was at work on a 13-inch triplet, the largest lens of this type ever attempted; the lens was later completed by Lundin for the Lowell Observatory and has become famous through its use in the discovery of the planet Pluto.

For his discoveries of comets, Metcalf received five medals. He also discovered a number of new variable stars, and 41

new minor planets. He was a member of the American Astronomical Society and a Fellow of the American Academy of Arts and Sciences. For many years he was Chairman of the Visiting Committee of Harvard Observatory, as well as a member of the Visiting Committee of the Ladd Observatory. It must be remembered that all these activities were in addition to the arduous duties of the pastor of a large church.

The third interest in Metcalf's life was associated with the World War. He became a secretary of the Young Men's Christian Association, and sought service at the front. By choice he shared the perils and discomforts of the private. His conduct endeared him to his associates, and he was cited for bravery at Château-Thierry.

Henry Gannett, 1829 *to* 1915.—Geographer, United States Geological Survey, 1882 to 1915. Dr. Gannett was assistant at the Observatory, 1870 to 1872.

Nathaniel S. Shaler, 1841 *to* 1906.—Professor of Geology, Harvard University. Beginning in 1871, Professor Shaler made an elaborate study of the surface of the moon from the viewpoint of a geologist, using the large refractor.

Henry M. Parkhurst, 1825 *to* 1908.—Parkhurst was a stenographer for the United States Senate from 1848 to 1856, and for the Superior Court, New York City, from 1871 to 1891. He was an able and enthusiastic amateur astronomer, carrying on researches on asteroids and variable stars for many years at his private observatory. His results are published in the Harvard Annals, **18**, No. 3, and **29**, Nos. 3 and 4, and appendix. He also made many contributions to scientific journals.

Dana P. Bartlett, 1863 *to* .—Professor Bartlett (Professor of Mathematics in the Massachusetts Institute of Technology) was an assistant at the Observatory in 1887, and took part in the expedition to Colorado (pp. 55–56).

Harry E. Clifford, 1866 *to* .—Professor Clifford (Gordon McKay Professor of Electrical Engineering, Harvard University) was an assistant at the Observatory in 1887, and also took part in the expedition to Colorado.

George Ellery Hale, 1868 *to* .—Dr. Hale, Honorary Director of the Mount Wilson Observatory, was a volunteer research assistant at the Observatory in 1889 to 1890.

Robert DeCourcy Ward, 1867 *to* .—Professor Ward, now Professor of Climatology in Harvard University, passed several months at the Arequipa branch of the Observatory in 1897. While there, he carried on meteorological research, and made an inspection of the various meteorological stations at that time maintained by the Observatory in southern Peru.

George K. Burgess, 1874 *to* .—Dr. Burgess, Director of the Bureau of Standards, Washington, was a student assistant at the Observatory in 1897.

Frederick W. Grover, 1876 *to* .—Professor Grover (Associate Professor of Electrical Engineering, Union College, Schenectady; Consulting Physicist, Bureau of Standards, Washington) was a volunteer observer at the Observatory in 1899.

Ralph A. Sampson, 1866 *to* .—Professor Sampson (formerly Professor of Mathematics in Durham University; Astronomer Royal for Scotland) discussed, at Professor Pickering's request, the photometric observations of Jupiter's satellites made at the Harvard Observatory from 1878 to 1903. The results of the discussion are given in Harvard Annals, **52**, Part 2, published in 1909.

Clarence A. Chant, 1865 *to* .—Professor Chant, now Professor of Astronomy in the University of Toronto, carried out volunteer research work on variable stars in 1916. His study of the light curve of W Virginis is given in Harvard Annals, **80**, No. 12.

Herbert C. Wilson, 1858 *to* .—Professor Wilson (Professor of Astronomy and Director Emeritus of the Goodsell Observatory, Carleton College) pursued research on variable stars at Harvard in 1916. His investigation of the light curve of T Andromedae is published in Harvard Annals, **80**, No. 8.

Jacobus C. Kapteyn, 1851 *to* 1922.—During the directorship of Edward C. Pickering, cooperation was effected between the

Harvard and Groningen Observatories in the execution of Kapteyn's systematic Plan of Selected Areas. The Harvard Observatory undertook to furnish durchmusterung plates of all the Selected Areas, visual and photographic magnitudes of the desired stars, and the classification of spectra. The reductions were all made under Professor Kapteyn's direction. The results of this cooperation are given in the Harvard Annals, **101**, **102**, and **103**. After Kapteyn's death in 1922, this cooperation was continued by his successor, Dr. van Rhijn.

Ejnar Hertzsprung, Professor of Astronomy, University of Leiden, Holland.—Professor Hertzsprung spent seven months in 1926 to 1927 at the Observatory in the study of short period variable stars on the Harvard photographs. He made 11,000 estimates of magnitude and obtained results bearing on the discovery, previously made by him, of a systematic relation of the form of the light curve to the length of period among typical Cepheid variables.

Some account has been given in Chapter VII of the cooperation of Professors Henry N. Russell, of Princeton, and Ernest W. Brown of Yale, in the photographic determination of the moon's position.

In recent years a number of volunteer research assistants have carried on various investigations at the Observatory. Among them may be mentioned Martha B. Shapley (Mrs. Harlow Shapley); Miss Margaret Harwood, Director of the Maria Mitchell Observatory at Nantucket; Dr. Priscilla Fairfield, Professor of Astronomy at Smith College; Dr. Theodore Dunham, of Mount Wilson Observatory; Dr. Donald H. Menzel, of Lick Observatory; Professor Issei Yamamoto, of Kyoto; Dr. Charles Lassovszky, of Budapest; Dr. Paul Davidovich, of Moscow; Professor S. D. Townley, of Stanford University; and Professor B. P. Gerasimovič, of the University of Kharkov, Russia.

CHAPTER XX

LIST OF OBSERVATORY STAFF MEMBERS

A LIST is given below of the members of the staff of the Observatory since its beginning. During the directorship of the Bonds and Winlock, the number of assistants did not exceed three or four at any time, and was often less. At first, the position of Assistant, formally appointed, was regarded as an important one and is so used in this list. The rank of First Assistant, in use at one time, was one of some distinction, fully equal to the present rank of Assistant Professor of Astronomy. Later the number of assistants has often been as high as 40, or even higher. Many of these, however, were students or others whose services, irregular and brief, consisted in the routine duties of the different departments of the Observatory. In general these have not been included in the list, but only those who were regularly employed in astronomical work for a year or more. The term of service occasionally includes a brief interval of absence. The list contains the names of both living and deceased members, to the end of 1927. It is divided into two sections; with a few exceptions, the first contains those members whose appointments were made by the Corporation, arranged in chronological order, and the second, those appointed by the directors, arranged in alphabetical order.

Members of the Observatory

Name	Position	Term of Service
Wiliam C. Bond	Director; Phillips Professor, 1849 to 1859	1839–1859
George P. Bond	Director; Phillips Professor, 1859 to 1865	1846–1865
Charles W. Tuttle	Assistant	1850–1854
P. Sydney Coolidge	Research Associate	1853–1860
Truman H. Safford	Assistant	1854–1865
Joseph Winlock	Director, Phillips Professor	1866–1875
Arthur Searle	Phillips Professor, 1887 to 1912	1868–1920
Charles S. Peirce	Assistant	1868–1875
William A. Rogers	Assistant Professor	1870–1886
Leonard Waldo	Assistant	1875–1880
Edward C. Pickering	Director; Phillips Professor, 1877 to 1887; Paine Professor, 1887 to 1919	1877–1919
Winslow Upton	Assistant	1877–1879
Oliver C. Wendell	Assistant Professor	1879–1912
John R. Edmands	Assistant	1880–1910
Seth C. Chandler	Research Associate	1880–1913
Mrs. Williamina P. Fleming	Curator of Astronomical Photographs	1881–1911
Abbott L. Rotch	Professor; Director, Blue Hill Meteorological Observatory	1886–1912
Willard P. Gerrish	Assistant Professor	1886–
*William H. Pickering	Assistant Professor	1887–
*†Solon I. Bailey	Phillips Professor, 1912 to 1925	1887–
Edward S. King	Phillips Professor, 1926 to	1887–
Miss Antonia C. Maury	Research Associate	1888–
Miss Annie J. Cannon	Curator of Astronomical Photographs	1896–
*Leon Campbell	Astronomer	1899–
Miss Henrietta S. Leavitt	Assistant	1902–1921
Harlow Shapley	Director, Paine Professor	1921–
Willard J. Fisher	Research Associate	1922–
Willem J. Luyten	Assistant Professor	1923–
*†John S. Paraskevopoulos	Assistant Professor	1923–
Miss Cecilia H. Payne	Astronomer	1923–
Boris P. Gerasimovič	Research Associate	1926–

MEMBERS OF THE OBSERVATORY.—(*continued*)

Name	Term of Service	Name	Term of Service
Miss Adelaide Ames	1923–	Henry Gannett	1870–1872
Miss Mary Applegate	1918–1920	R. W. Gifford	1886–1888
(Mrs. Beach)		Miss Edith F. Gill	1889–
William H. Atwill	1888–1902	Miss Mabel A. Gill	1892–
Edward P. Austin	1869–1871	Frederick W. Grover	1899
*Hinman C. Bailey	1893–1902	Asaph Hall	1857–1862
*Marshall H. Bailey	1888–1891	Miss S. H. Hall	1897–1900
Darsie C. Bard	1899–1900	(Mrs. Bonesteele)	
Dana P. Bartlett	1887	Miss Mildred L. Hannon	1927–
Philip S. Bates	1911–1914	Miss Maude E. Harriman	1900–1905
Robert Black	1888–1890	Miss Margaret Harwood	1907–1912
*Herbert E. Blackett	1908–1911	Miss Marian A. Hawes	1912–1918
*L. C. Blanchard	1916–1918	Guy Hill	1904–1905
*†Miss Dorothy W. Block	1917–	*Philip P. Hill	1905–1911
(Mrs. Paraskevopoulos)		*Frank E. Hinkley	1907–1918
Miss Selina C. Bond	1879–1920	Miss Lillian L. Hodgdon	1889–
Frank L. Bowie	1904–	Frank S. Hogg	1926–
Miss Constance D. Boyd	1926–	Miss Helen E. Howarth	1923–
David E. Brand	1911–1912	Miss Mary B. Howe	1924–1925
Frederick E. Brasch	1902–1904	Miss Mary E. Howe	1907–1909
Miss Sarah E. Breslin	1898–1912	A. Jansen	1892–1894
Miss Grace R. Brooks	1906–1920	J. Arthur Jennison	1889–1891
Wilbur V. Brown	1879–1883	Everett T. King	1911–1916
George K. Burgess	1897	Harold S. King	1916–1921
Miss Irma W. Caldwell	1926–	Samuel P. Langley	1865–1866
Miss Florence M. Campbell	1925–	Anson S. Leard	1905–1908
Leon Campbell, Jr.	1921–1927	Miss Evelyn F. Leland	1889–1925
Miss Alta M. Carpenter	1906–1920	Miss Helen M. Lewis	1927–
Samuel C. Catterall	1908–1911	(Mrs. Thomas)	
Miss Geraldine E. Clark	1926–1927	Augustus McConnel	1870–1871
Harry E. Clifford	1887	Joseph F. McCormack	1872–1880
*William B. Clymer	1895–1900	Charles E. McCullar	1900–1905
Harold R. Colson	1895–1905	Miss Amy J. McKay	1891–1906
Harold St. C. Cook	1916–1918	Miss Johanna C. S. Mackie	1903–1920
Ernest R. Cram	1894–1902	*Edmund S. Manson	1902–1907
Leland E. Cunningham	1925–	Miss Frances Cooper-Marshal	1926–1927
Miss Florence Cushman	1888–	Miss Annie E. Masters	1887–1889
Arthur W. Cutler	1880–1884	Miss Genevieve F. Mathews	1912–1916
Miss Mary Daniel	1927–	*H. Mechelhof	1893–1894
Robert S. Davidson	1893–1898	Miss Marion F. Michaelis	1900–1906
*Andrew E. Douglass	1890–1894	Miss Jenka Mohr	1927–
*Luis Duncker	1890–1894	*Juan C. Muñiz	1922–1925
John A. Dunne	1888–1909	*Juan E. Muñiz	1895–1925
Miss Madalen R. Dwyer	1926–	Miss Muriel E. Mussells	1927–
Clifford C. Eaton	1881–1884	Miss Sylvia F. Mussells	1927–
Mrs. I. W. Eddy	1889–1904	T. Oliver Olsen	1914–1917
Miss Margaret B. Evans	1927–	Miss Mollie E. O'Reilly	1906–1918
Miss Nettie A. Farrar	1881–1885	(Mrs. Sloan)	
Frederick E. Fowle	1888–1890	Philip G. O'Reilly	1910–1914
Miss Carol G. Fox	1927–	*Harold I. Peckham	1912–1915
John H. Freese	1901–1902	Thomas E. Powe	1890–1893
*Royal H. Frost	1896–1908	Miss Susan Raymond	1916–1917

MEMBERS OF THE OBSERVATORY.—(*continued*)

Name	Term of Service	Name	Term of Service
William M. Reed	1890–1900	*George T. Vickers	1890–1893
John Ritchie	1883–1892	*Elias Vieyra	1889–1900
Mrs. R. T. Rogers	1875–1898	*C. J. G. Vogel	1910–1911
Miss Helen J. Roper	1926–	Edward B. Waite	1894–1900
Willard I. Rowe	1907–1910	Frank Waldo	1878–1881
Miss Jennie T. Rugg	1887–1889	Miss Arville D. Walker	1906–
John D. Runkle	1853	Miss Emma E. Walker	1912–1918
Miss R. G. Saunders	1875–1888	Miss Margaret L. Walton (Mrs. Mayall)	1924–
Miss Helen B. Sawyer	1926–		
Henry A. Sawyer	1920–	*George A. Waterbury	1893–1898
Arthur R. Sayer	1927–	Miss Ruth C. Waterbury	1907–1910
†L. G. Schultz	1909–1910	William F. H. Waterfield	1926–
George M. Searle	1866–1868	Miss Louisa D. Wells	1887–
Miss Katharine Searle	1904–1912	William W. White	1900–1909
Howard R. Shaw	1906–1908	Miss Marion C. Whyte	1911–1913
*I. Franklin Snow	1906–1907	Robert W. Willson	1874–1875
Miss Beatrice L. Sparks	1923–1924	Miss Harvia H. Wilson	1924–1925
Miss Harriet I. Stevens	1891–1910	Miss Jane B. Wilson	1912–1913
Miss Ida M. Stevens	1904–1909	Hobart W. Winkley	1887–
Miss Mabel C. Stevens	1888–1906	Miss Anna Winlock	1875–1903
*Delisle Stewart	1896–1902	Miss Louisa Winlock	1886–1915
Miss Nellie C. Storin	1887–1889	William C. Winlock	1876–1880
Rufus O. Suter	1923–1926	Miss E. Gertrude Wolffe	1893–1899
Miss Henrietta H. Swope	1926–	Miss Doris Wood (Mrs. Wills)	1927–
Miss Helen Symonds	1925–1926		
É. Léopold Trouvelot	1872–1874	Miss Ida E. Woods	1893–
Horace P. Tuttle	1858–1862	*Benjamin F. Wyeth	1902–1905

* In Peru.
† In South America.

CHAPTER XXI

BENEFACTORS OF THE OBSERVATORY

THE foundation and development of the Harvard Observatory has been due in large part to private gifts. Although the beginnings of the Observatory at the Dana House were chiefly the result of University enterprise and especially of the enthusiastic interest of President Quincy, the establishment of the new Observatory on a firm foundation was accomplished through the generosity of the public-spirited business men of Boston, and patrons of science elsewhere.

Past and Present Benefactors.—A consideration of the benefactors of the Observatory should include some mention of men not generally regarded as such. The Bonds, especially W. C. Bond, by the arduous service which they gave for the first six years without salary, alone made possible the establishment and maintenance of the Observatory at that time. W. C. Bond gave not only his time but much of the early equipment. Edward C. Pickering, during his long directorate, frequently made contributions toward the running expenses of the Observatory. Here, also, should be mentioned the name of the Reverend Joel H. Metcalf, who gave the time and skill necessary to grind several photographic lenses, which have been of much value to the Observatory.

The contributions of the University to the Observatory have been large. At the beginning, the Corporation undertook to provide the necessary grounds and buildings for the Dana House Observatory, and to devote to its use whatever apparatus was in the possession of the College. The University, however, had no funds with which to give it an endowment or provide for its expenses. Nevertheless, as shown by the Report of the

Treasurer of Harvard College in 1846, the University advanced considerable sums toward the completion of the new Observatory and its equipment.[1] Recently the University contributed about $200,000 toward the transfer of the Boyden Station to South Africa and toward its equipment, and the International Education Board (Rockefeller) gave an equal amount.

The American Academy of Arts and Sciences has often shown an interest in the Observatory, and in the early and difficult years, in 1839 and again in 1843, contributed several thousand dollars for the purchase of apparatus. A thousand dollars was also given at that time by the Boston Society for the Diffusion of Useful Knowledge. The greater part of the funds, however, which have made possible the growth of the Observatory, have come from private individuals. The gifts began with the building and equipment of the new Observatory, when Mr. David Sears offered $5000 for a tower to contain the large refractor, on the condition that $20,000 should be contributed by others for the purchase of the telescope. This sum was promptly raised by subscriptions made chiefly in Boston. Mr. Sears later gave an additional $5000.

The first large gift toward the permanent endowment of the Observatory came in 1848 on the death of Edward Bromfield Phillips, a college classmate of George P. Bond, who bequeathed to the Observatory $100,000, a large sum for those days. The income from this fund first permitted the payment of salaries, and also provided something toward other necessary expenses.

Citizens of Boston contributed $5000 toward the running expenses of the Observatory in 1846, a time of serious financial difficulties. Again in 1851, several thousand dollars were contributed, by many donors, to meet urgent needs. In 1855 the Observatory received the fund of $10,000 from President Quincy, given in honor of Josiah Quincy, Jr. This fund has been of special aid in publication. Nathaniel Bowditch had been influential in the establishment of the Observatory, and

[1] H. A., I, xc, 1846.

his son, J. Ingersoll Bowditch, was for many years a firm and generous friend.

At the beginning of the administration of Edward C. Pickering, the income of the Observatory was still scant and inadequate, and appeals for aid were frequent. Many thousand dollars were thus raised to meet the increasing expenses. A much larger activity was made possible in 1886 with the Paine Fund, which in all amounted to about $400,000; and in 1887 by the Boyden Fund of about $230,000. The contributions of Mrs. Henry Draper during her life, and her bequest in 1914 for the work of the Henry Draper Memorial, amounted to several hundred thousand dollars.

In 1898, two bequests without restrictions were received, one of $20,000 by the will of Charlotte Maria Haven, and one of $25,000 by the will of Eliza Appleton Haven. In 1902, an anonymous gift of $20,000 was received from a donor who preferred not to have his name announced.

The number of small contributors to the Observatory has been numerous—as many as 300 since the beginning of its history. Brief sketches of the lives of the more prominent deceased benefactors are given below.

The Observatory is fortunate, also, in its friends now living. The following deserve special gratitude, since their gifts have been carefully and wisely directed in aid of worthy current investigations, for the prompt publication of results which otherwise would have been delayed, and for the foundation of astronomical fellowships:

Mr. George R. Agassiz, of Boston
Mrs. James R. Jewett, of Cambridge
Mrs. Charles S. Hinchman, of Philadelphia
Mr. Gerard Swope, of New York
Mr. C. W. Elmer, of New York
Mrs. C. W. Elmer, of New York

Edward Bromfield Phillips, 1826 (*about*) *to* 1848.—The first considerable sum given for the maintenance of the Observatory was the bequest of Edward B. Phillips, who died in 1848.

Mr. Phillips entered Harvard College in 1841, and was graduated in 1845. He was a classmate of George P. Bond, which probably accounts in part at least for his keen interest in astronomy. It was found after his unfortunate death in 1848 that he had bequeathed $100,000 to the Observatory. It is difficult now to appreciate how much this meant to those who were at that time struggling to maintain the reputation of the Observatory with an utterly inadequate income. This really munificent gift saved the institution from possible failure, and started it afresh on an upward career.

In honor of the donor, the Corporation early established the Phillips Professorship of Astronomy, and gave to the library connected with the Observatory the name "Phillips Library."

Robert Treat Paine, 1803 *to* 1885.—Robert Treat Paine was born in Boston, October 12, 1803, and died in Brookline, June 3, 1885. He was a grandson of Robert Treat Paine, one of the signers of the Declaration of Independence. Mr. Paine had from boyhood until old age an intense interest in astronomy. He always remembered the comet of 1811, which he maintained was not equalled by any comet which he observed later.

By profession Mr. Paine was a lawyer, but the great passion of his life was for astronomy and meteorology. For nearly 60 years he himself made a continuous series of meteorological observations in his home in Boston and later in Brookline.

Mr. Paine's astronomical observations were made with portable instruments. He had exceptional skill with the sextant, and was appointed chief engineer of the survey of the State of Massachusetts. His special astronomical interest was in the motion of the moon as determined by occultations and eclipses. During his life he computed over 2000 occultations and observed many of them. During 60 years no solar eclipse occurred near Boston which was not observed by him if the weather permitted. In all he observed in different places nine total or annular eclipses of the sun. To observe the total eclipse of 1880, although more than seventy six years of age,

he travelled alone to California. At the age of eighty two he was planning to observe the eclipse of March 16, 1885, in Montana, and was prevented only by sickness and approaching death. He showed his devotion to astronomy by bequeathing his entire fortune, amounting to more than a quarter of a million dollars, to the Harvard Observatory. In his honor the Paine Professorship of Practical Astronomy was established, and since then that professorship has been conferred on the Director of the Observatory. Formerly the director held the title of Phillips Professor of Astronomy, a place which has later been held by the chief assistant.

Uriah Atherton Boyden, 1804 *to* 1879.—Mr. Boyden, for many years a mechanical engineer of Boston, was born in Foxborough, Massachusetts, in 1804, and died in Boston in 1879. His devotion to science was shown in various ways during his life and by his bequest to astronomy at his death.

Mr. Boyden, in 1859, deposited with the Franklin Institute of Philadelphia the sum of $1000, to be awarded as a prize to any resident of North America who should determine by experiment whether or not all rays of light and other physical rays are transmitted with the same velocity. The Franklin Institute advertised the offer for many years, and 25 or 30 papers were presented, none of which was deemed worthy of the prize. At length in 1907, nearly half a century after the offer was first made and many years after Boyden's death, the prize was awarded to Dr. Paul R. Heyl, then of Philadelphia. Dr. Heyl found by elaborate experiments on Algol that, in a distance of 40 light years, the difference of the velocities of the ultra-violet and visual rays could not exceed one part in two hundred and fifty thousand.

In 1862, Mr. Boyden published in the Journal of the Franklin Institute, Volume XLIV, a paper entitled "On Explosions produced by Nitre in Burning Buildings, etc."

Mr. Boyden left by will a sum amounting to about $230,000 for the establishment of a mountain observatory at such an altitude as to avoid, so far as possible, the ill effects of the

earth's atmosphere. The fund was placed in the hands of a Board of Trustees, who, in 1887, transferred it to the President and Fellows of Harvard College for the use of the Observatory. The southern station of the Observatory, formerly at Arequipa, Peru, and now at Mazelspoort, South Africa, is known as the "Boyden Station."

Miss Catherine Wolfe Bruce.—About 1888, Miss Bruce, of New York City, became interested in Professor Pickering's plan for the construction of a powerful photographic doublet. As a result of this interest she gave, in 1889, $50,000 for the construction and care of such an instrument. Several years were needed in which to secure the glass discs and to do the grinding. The resulting telescope, a photographic doublet of 24 inches aperture, was called the "Bruce Telescope." It is described in Chapter IV.

Experimental work was begun with this instrument late in 1893. In 1895 it was removed to Arequipa, Peru, where for more than 30 years it gave important results. Remounted and transferred to the new Boyden Station in South Africa, it still has many years of great usefulness.

Miss Bruce showed her interest in astronomy by numerous smaller gifts to the Observatory and to astronomers elsewhere. In 1890 she gave $6000 to be distributed during the year in aid of astronomical science anywhere. Through the aid of Professor Pickering, sums of $500 or less were contributed to various investigators in different countries. She found much pleasure in the contacts thus made with prominent astronomers.

Miss Bruce gave assistance also to Barnard at the Yerkes Observatory and Wolf at Heidelberg, in the purchase of photographic telescopes; to Weinek at Prague in the publication of his Moon-Atlas; and to the Lick Observatory for the purchase of photometers. In 1897 she presented a fund of $2500 to the Astronomical Society of the Pacific, to make possible the yearly award of a gold medal "for distinguished service to Astronomy." The first award was made in 1897, to Simon Newcomb.

Miss Bruce, whose health had always been delicate, died in New York City in 1900.

Mrs. Henry Draper.—Anna Palmer Draper, daughter of Courtlandt Palmer and wife of Dr. Henry Draper, died in New York City, December 8, 1914.

Mrs. Draper, from the time of her marriage until the sudden death of Dr. Draper in 1882, was an enthusiastic and unselfish companion and aid in all his investigations. Dr. Draper was a pioneer in astrophysics, and had a private laboratory and an observatory. It is said that he never went to his observatory without Mrs. Draper, his sympathetic and intelligent assistant.

Mrs. Draper, after the death of her husband, planned at first to establish an observatory in New York City, as a memorial to him. She finally decided, however, to found a department at the Harvard Observatory, for the study of the spectra of the stars. This research became known as the "Henry Draper Memorial." For the prosecution of this work, Mrs. Draper gave large sums during many years, and at her death bequeathed a substantial amount to increase the permanent endowment of the Observatory. Mrs. Draper was by no means satisfied with the gift of money, but always exhibited a keen and intelligent interest in the progress of the investigations.

The results of the Draper Memorial have been not only voluminous but of immense value in the progress of astronomy. The largest publications concerned in it are: The Draper Catalogue, Annals, **27**, giving a classification of the spectra of 10,351 stars; and the Henry Draper Catalogue of more than 200,000 stars, covering the whole sky, occupying Volumes **91** to **99** of the Annals.

Charles Robert Cross, 1848 *to* 1921.—Professor Cross was born at Troy, New York, on March 29, 1848. His great-grandfather, Robert Cross, was a major in the American Army of the Revolution.

Mr. Cross entered the sophomore class of the Massachusetts Institute of Technology in 1867, and obtained his training under President Rogers and Professor Edward C. Pickering.

On his graduation in 1870, he became Instructor in Physics at that institution, and was made Professor of Physics in 1875. From then until his retirement in 1917 he was an influential factor in the development of the Institute.

Mr. Cross served as scientific expert for the Bell Telephone Company. Early recognizing the importance of electrical development, he gave the first course in Electrical Engineering in this country, and wrote many papers on electrical subjects. He was a member of various scientific societies, and for many years was Chairman of the Rumford Committee of the American Academy of Arts and Sciences.

Mr. Cross had a keen love of astronomy and generally attended the annual meetings of the American Astronomical Society, although seldom or never taking part in the proceedings. For many years he was a member of the Visiting Committee of the Harvard Observatory. His deep interest in the Observatory may be traced, at least in part, to his profound regard for Edward C. Pickering, its Director, whose pupil in physics he had been at the Institute. This may account for the bequest of the greater part of his fortune to the Harvard Observatory. The bequest will finally amount to more than a hundred thousand dollars.

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